

**PATH-DEPENDENCIES FACED BY SELECT POLICIES TOWARD
SOLID-STATE LIGHTING**

A Dissertation
Presented to
The Academic Faculty

by

Alexander M. Smith

In Partial Fulfillment
of the Requirements for the Degree
Doctorate of Philosophy in the
School of Public Policy

Georgia Institute of Technology
May 2020

COPYRIGHT © 2020 BY ALEXANDER M. SMITH

**PATH-DEPENDENCIES FACED BY SELECT POLICIES TOWARD
SOLID-STATE LIGHTING R&D**

Approved by:

Dr. Marilyn A. Brown, Advisor
School of Public Policy
Georgia Institute of Technology

Dr. Alan Porter
School of Public Policy
Georgia Institute of Technology

Dr. Matej Drev
Coil Technologies, Inc.

Dr. Mark Z. Taylor
School of Public Policy
Georgia Institute of Technology

Dr. Steven W. Usselman
School of History and Sociology
Georgia Institute of Technology

Date Approved: December 9, 2019

Dedicated to the memory of Iona Malmborg

ACKNOWLEDGEMENTS

First and greatest thanks to my good friend and colleague Jonah Bea-Taylor. He showed the most intellectual merit of anyone I encountered in all of Georgia Tech, and I've learned more from him than from any class through our many stimulating discussions. I am most proud, grateful, and fortunate have such an ally.

Further thanks to Jade Charnigo, whose work is worth the salaries of many professors and whose kindness and generosity kept the School of Public Policy from imploding on itself.

Thanks to Dr. Elsa Reichmanis for believing in independent inquiry that addresses substantive and important questions and for supporting skill expansion beyond the easy stuff, beyond the mundane imitation, into the domain of real knowledge-building. And for being a grounded and very effective leader. Thanks to my IGERT team for braving adversity together and proving that quality work without big names attached can get published.

Thanks to the doctoral defense committee for reading and approving this dissertation. Special thanks to Dr. Matej Drev for serving on the committee while innovating in Silicon Valley, and special thanks to Dr. Steve Usselman for excellent insights and inspiration and for serving as the committee member outside the School of Public Policy.

Thanks to many Youtubers and SoundCloud members whose uploads accompanied me through many long hours – special thanks to anyone who uploaded OSTs from the Command & Conquer, Half-life/Portal, and WipeOut franchises.

Thanks to my parents and brother, Dr. Baxter Smith, who continued to provide encouragement whenever I came up for air long enough to fill them in. Big thanks to the FERC fam – everyone who started with me in the OEPI 2016 cohort and is still hanging in there.

And deepest thanks to Emily for her enduring support and love and for giving me space to get this finished. I love you.

TABLE OF CONTENTS

| | |
|--|--------------|
| ACKNOWLEDGEMENTS | iv |
| LIST OF TABLES | x |
| LIST OF FIGURES | xiii |
| SUMMARY | xviii |
| CHAPTER 1. Introduction | 1 |
| 1.1.1 Chapter 3: policies for inter-firm collaboration and SSL technology development | 2 |
| 1.1.2 Chapter 4: patent licensing policies for federally funded SSL R&D | 3 |
| 1.1.3 Chapter 5: Climate change mitigation policies and SSL product adoption | 4 |
| 1.2 Contributions to academic debates | 5 |
| 1.3 Terminology: Distinguishing “innovation” from “technology development” | 8 |
| CHAPTER 2. review of Path-dependency studies and the history of solid-state lighting R&d | 10 |
| 2.1 Literature on path-dependencies in R&D and energy systems | 10 |
| 2.1.1 Path-dependency and R&D in firms, regions, and sectors | 10 |
| 2.1.2 Path-dependency and energy systems | 14 |
| 2.1.3 Gaps identified in the path-dependency literature | 17 |
| 2.2 A brief history of SSL R&D | 19 |
| 2.2.1 1940s through 1970s: Solid-state lighting occupies small niche applications | 19 |
| 2.2.2 1980 to 2000: New applications for solid-state lighting and the foundations of white LEDs | 23 |
| 2.2.3 Policy and Technology converge: Emissions reduction policies create new opportunity for solid-state lighting technologies | 29 |
| 2.2.4 The DOE SSL program | 33 |
| 2.2.5 Current excitement around SSL’s potential for driving innovation rests primarily on technology | 34 |
| CHAPTER 3. Path-dependencies in inter-firm R&D collaboration: Philips, Hewlett-Packard, and the Lumileds joint venture | 38 |
| 3.1 Research Question | 38 |
| 3.1.1 Independent Research: HP had prior experience with LEDs, not Philips | 39 |
| 3.1.2 The forming of Lumileds: HP and Philips’ knowledge complementarity | 42 |
| 3.2 Literature Review | 42 |
| 3.2.1 A Path-dependency theory of firm behavior: Evolutionary Economics claims Core Capabilities determine a firm’s decisions | 43 |
| 3.3 Hypothesis and rival hypotheses | 45 |
| 3.3.1 Hypothesis H1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent lacked Core Capabilities suitable for inter-firm collaboration | 45 |

| | | |
|-------------------|--|------------|
| 3.3.2 | Rival hypothesis R1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent's expected net returns on SSL technology development fell below HP/Agilent's desired net returns from remaining in the joint-venture | 46 |
| 3.4 | Methodology | 46 |
| 3.4.1 | Testing hypothesis H1: Examining the early histories and Core Capabilities of HP and Philips, as well as changes to the business environment | 46 |
| 3.4.2 | Testing rival Hypothesis R1: Examining the life of Lumileds and HP's expected net returns from SSL technology development | 47 |
| 3.5 | Findings | 48 |
| 3.5.1 | Findings for hypothesis H1 on Core Capabilities | 48 |
| 3.5.2 | Findings for rival hypothesis R1 on HP's expected net returns from SSL technology development | 74 |
| 3.6 | Conclusions | 95 |
| 3.6.1 | Comparing the findings for each hypothesis: which best explains HP's decision to leave Lumileds? | 95 |
| 3.6.2 | Synthesis: Organizational Capabilities explain Agilent's sale of Lumileds to Philips | 97 |
| 3.6.3 | Lessons for policy-making | 97 |
| CHAPTER 4. | Path-Dependencies and Patent Licensing: the us department of energy's compulsory Licensing Policy | 99 |
| 4.1 | Research Question | 99 |
| 4.1.1 | Origins of the compulsory licensing policy: The Energy Policy Act of 2005's directive and the NGLIA | 100 |
| 4.1.2 | Details of the DOE SSL Program's compulsory licensing policy | 104 |
| 4.2 | Literature review: Prior findings on patent licensing and patent production | 106 |
| 4.2.1 | Prior studies analyzing patent licensing policies and patent production | 106 |
| 4.2.2 | Path-dependency and patenting: The Theory of Appropriability Regimes | 113 |
| 4.3 | Hypothesis and rival hypotheses on the effects of the DOE SSL's compulsory licensing policy on patent production | 114 |
| 4.3.1 | Hypothesis H1: The compulsory licensing policy decreased patenting among inventors whose work was funded by the DOE SSL program | 114 |
| 4.3.2 | Hypothesis H1a: The compulsory licensing policy reduced the patenting of researchers at smaller firms more than the patenting of researchers at larger firms. | 114 |
| 4.3.3 | Rival hypothesis R1: The compulsory licensing policy had no effect on inventors whose work was funded by the DOE SSL program | 114 |
| 4.3.4 | Rival hypothesis R2: Any observed differences between researchers subject to the compulsory licensing policy and researchers not subject to the compulsory licensing policy are due to age differences between the two groups and not to the effects of the compulsory licensing policy. | 115 |
| 4.3.5 | Hypothesis H2: The compulsory licensing policy decreased patenting by researchers facing high Appropriability Regimes more than it decreased patenting by researchers facing low Appropriability Regimes in the industries of the researchers' respective firms. | 115 |
| 4.4 | Methodology | 116 |
| 4.4.1 | Advantages of comparing patent productivity between sampled researchers | 116 |

| | | |
|--|---|------------|
| 4.4.2 | Gathering data on patents produced by DOE SSL PIs | 117 |
| 4.4.3 | Gathering data on DOE SSL PIs themselves | 120 |
| 4.4.4 | Advantages of chosen data-collection methodology versus alternatives | 127 |
| 4.4.5 | Results of data filtering: Reducing patents to only those made by authors with professional background information available online | 129 |
| 4.5 | Data analysis and findings | 132 |
| 4.5.1 | Aggregations of patent data | 132 |
| 4.5.2 | Regression models fitted to patent data | 147 |
| 4.5.3 | Summary of findings and comparisons to initial hypotheses | 162 |
| 4.6 | Conclusions | 164 |
| 4.6.1 | Conclusions on compulsory licensing's interaction with Appropriability Regimes | 166 |
| 4.6.2 | Conclusions on path-dependency's lessons for lighting R&D policy | 167 |
| 4.6.3 | Who should care and why | 170 |
| CHAPTER 5. Path-dependencies in lighting technology and electric power infrastructure | | 172 |
| 5.1 | Research question | 172 |
| 5.2 | Literature Review | 173 |
| 5.3 | Hypotheses | 177 |
| 5.3.1 | Hypotheses 1: Sectors whose building types are the most intensive users of lighting will exhibit the greatest LED adoption | 177 |
| 5.3.2 | Hypothesis 2: Holding LED adoption constant, power sector outcomes will vary by region due to the influence of path-dependent factors | 178 |
| 5.3.3 | Hypothesis 3: Greater LED adoption results in lower Total Resource Cost | 182 |
| 5.3.4 | Hypothesis 4: Greater LED adoption displaces high-emitting power sources | 183 |
| 5.4 | Methodology for testing hypotheses | 183 |
| 5.4.1 | Using GT-NEMS to model power sector and consumer sector interactions | 185 |
| 5.4.2 | Updating GT-NEMS to reflect the Clean Power Plan and contemporary policies | 194 |
| 5.4.3 | Scenario nomenclature | 207 |
| 5.5 | Results from methodology | 207 |
| 5.5.1 | Demand-side results: LED adoption nationally and among four census divisions | 207 |
| 5.5.2 | Supply-side results: Power sector investment and operations for four regions | 222 |
| 5.5.3 | Grouped results figures | 234 |
| 5.6 | Conclusion | 238 |
| 5.6.1 | Summary of main findings | 238 |
| 5.6.2 | Why the findings are novel and interesting | 239 |
| 5.6.3 | Takeaways for policy-making | 241 |
| CHAPTER 6. Conclusions and prospects on Lighting technology paths taken and yet to be taken | | 244 |
| 6.1 | Lessons from Path-dependency analyses of lighting innovation policies | 244 |
| 6.1.1 | Path-dependency in firms: Core Capabilities can frustrate policies fostering inter-firm collaboration for technology development | 244 |

| | | |
|------------|--|------------|
| 6.1.2 | Path-dependency in patenting: Appropriability Regimes can frustrate policies fostering technology sharing through patent production and licensing | 246 |
| 6.1.3 | Path-dependency in buildings and power grids: Existing infrastructure can frustrate policies for lighting adoption and electricity cost reductions | 247 |
| 6.2 | Implications for Path-dependency: Contributions to existing academic debates | 249 |
| 6.3 | Where is solid-state lighting going to go next? | 252 |
| 6.3.1 | Near-term outlook for solid-state lighting technology | 253 |
| 6.3.2 | Where are markets for solid-state lighting products going next? | 257 |
| 6.4 | What will lighting contribute to US economic growth and development? | 262 |
| 6.4.1 | Geographic distribution of the solid-state lighting industry | 262 |
| 6.4.2 | Current state of the global solid-state lighting industry and its markets | 266 |
| 6.4.3 | The Department of Energy's view on appropriating the economic benefits of SSL | 270 |
| 6.4.4 | Can SSL contribute to US economic growth and global competitiveness? | 272 |
| | References | 275 |

LIST OF TABLES

| | | |
|----------|--|-----|
| Table 1 | Examples of LED niche applications between 1960 and 1970. Source: Sanderson & Simons, 2014 | 20 |
| Table 2 | Between 1945 and 1981, the top ten R&D organizations ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014 | 21 |
| Table 3 | From 1981 to 2010, new applications for LED technologies and the firms that pioneered each application. Source: Sanderson & Simons, 2014 | 26 |
| Table 4 | Between 1982 and 1991, the top ten R&D organizations ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014 | 28 |
| Table 5 | Between 1992 and 2001, the top ten firms ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014 | 29 |
| Table 6 | Inter-firm collaboration ranking results from Hagedoorn & Schakenraad (1992). | 70 |
| Table 7 | Membership in Next Generation Lighting Industry Alliance, 2003-2014. Source: Wayback Machine research; NGLIA and DOE documents | 102 |
| Table 8 | Counts and proportions of patents, investigators, and patents granted to investigators post-funding produced by the study's data collection procedure. | 131 |
| Table 9 | Counts and proportions of patents granted before and after funding of each principal investigator | 132 |
| Table 10 | Total patents produced by sample investigators and percentages of total patents with breakouts by funding status | 134 |
| Table 11 | Average patenting per investigator, 1996 to 2014, categorized by funding status and firm size | 143 |
| Table 12 | Statistics for the best-fitting regression model | 151 |
| Table 13 | Summary of hypotheses and findings of the study | 164 |

| | | |
|----------|--|-----|
| Table 14 | List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector | 197 |
| Table 15 | continued: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector | 198 |
| Table 16 | continued: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector | 199 |
| Table 17 | Table of paired census divisions with NEMS EMM regions for analysis | 206 |
| Table 18 | List of Scenario names with descriptions of each | 207 |
| Table 19 | Service Demand met by LEDs in New England under the CPP+Subsidy and CPP-only cases | 208 |
| Table 20 | Service Demand met by LEDs in Mid Atlantic under the CPP+Subsidy and CPP-only cases | 211 |
| Table 21 | Service Demand met by LEDs in West South Central under the CPP+Subsidy and CPP-only cases | 214 |
| Table 22 | Service Demand met by LEDs in Pacific region under the CPP+Subsidy and CPP-only cases | 217 |
| Table 23 | Summary of comparisons between LED adoption trends observed in each of the four regions | 222 |
| Table 24 | Summary of electric power sector trends resulting from LED adoption observed in each of the four regions | 233 |
| Table 25 | Hypotheses, findings, and decision to reject or fail to reject each hypothesis | 239 |
| Table 26 | The LED Supply Chain - LED Die, LED Package, and Luminaire Manufacturers. Source: US Department of Energy, 2015 | 264 |
| Table 27 | The LED Supply Chain - Equipment and Materials Suppliers (continued over two segments). Source: US Department of Energy, 2015 | 265 |

| | | |
|----------|--|-----|
| Table 28 | Ranking of LED Manufacturers by Revenue: The Largest 10 Players in the LED Industry Saw Their Revenues Shrink or Stay Level. Source: Stephanie Pruitt, 2016, presentation at Strategies in Light, Santa Clara, CA, March 1-3 | 269 |
|----------|--|-----|

LIST OF FIGURES

| | | |
|-----------|--|-----|
| Figure 1 | A hypothetical technology multi-path map for dye-sensitized solar cells, showing an example of how the Path-dependency Framework can be applied to forecasting. Source: (Porter et al., 2010) | 14 |
| Figure 2 | Contrary to the anti-collaborative period of the 1940s, 1950s, and 1960s, the number of R&D-focused inter-firm collaborations (here the term “alliances” is used) increased dramatically throughout the 1970s and 1980s. Source: (David C. Mowery & Rosenberg, 1989) | 64 |
| Figure 3 | Structure of collaborative partnerships between firms between 1980 and 1984. Source: Original figure from Hagedoorn & Schakenraad (1992) | 71 |
| Figure 4 | Structure of collaborative partnerships between firms between 1985 and 1989. Source: Original figure from Hagedoorn & Schakenraad (1992) | 72 |
| Figure 5 | Forecast market growth for LEDs and other optoelectronic semiconductors. Source: (Mills, 2001) | 89 |
| Figure 6 | Market leaders in the sales of LED lamps and displays. Source: (Mills, 2001) | 90 |
| Figure 7 | Forecast of high-brightness LED market’s sales revenues for 2004-2009, as calculated by Strategies Unlimited in 2005. Source: (Costlow, 2005) | 92 |
| Figure 8 | Applications for high-brightness LED products in 2005, as calculated by Strategies Unlimited. Source: (Costlow, 2005) | 93 |
| Figure 9 | Total patents granted to investigators before and after being funded by the DOE SSL program | 135 |
| Figure 10 | Investigator affiliations during the analysis period. The results sometime exceed the number of sample investigators because, in a given year, each investigator may have more than one affiliation. | 136 |

| | | |
|-----------|--|-----|
| Figure 11 | Investigator affiliations during the analysis period. “USA” represents affiliations with US-based organizations; “EU” for the European Union; “JPN” for Japan; and “EastAsia_other” for China, South Korea, and Taiwan | 137 |
| Figure 12 | Time series of total sample investigators per year. An investigator “enters the sample” in the earliest year for which adequate background information on the investigator is available. | 138 |
| Figure 13 | Time series of patents per investigator, with breakouts by whether the patents came from a funded investigator (i.e. after program funding) or an investigator who had yet to be funded (i.e. before program funding) | 139 |
| Figure 14 | Average patents-per-investigator categorized by small-firm investigators and large-firm investigators. | 141 |
| Figure 15 | Average patents per investigator for small firms | 142 |
| Figure 16 | Average patents per investigator for large firms | 143 |
| Figure 17 | Raw distribution of observed values for patents produced by a given investigator-year across all sample data, categorized by investigator funding status. | 145 |
| Figure 18 | Data from Figure 17, restricted only to patent production values of 6 or greater (provided for clarity into distribution of less-frequently-observed patent production values). | 146 |
| Figure 19 | Distribution of observations across values of patents-per-investigator-year, with fitted exponential distribution superimposed | 147 |
| Figure 20 | Coefficients and 99% confidence intervals for the best-fitting regression model | 152 |
| Figure 21 | 99% confidence intervals for the model’s coefficients applied to the LARGE_FIRM, NE, and SubjectToCL variables | 155 |
| Figure 22 | 99% confidence intervals for the model’s coefficients applied to the SMALL_FIRM, California, and SubjectToCL variables | 157 |
| Figure 23 | 99% confidence intervals for the model’s coefficients applied to the LARGE_FIRM, EU, and SubjectToCL variables | 159 |

| | | |
|-----------|--|-----|
| Figure 24 | 99% confidence intervals for the model's coefficients applied to the Lighting, Materials, and SubjectToCL variables | 162 |
| Figure 25 | Percent of illuminated floorspace (x-axis) by building type (y-axis). Source: US Energy Information Administration, 2017 | 178 |
| Figure 26 | For New England, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types | 209 |
| Figure 27 | Absolute amount of LED increase attributed to each building type for select years | 210 |
| Figure 28 | For Mid-Atlantic, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types | 212 |
| Figure 29 | Absolute amount of LED increase attributed to each building type for select years | 213 |
| Figure 30 | For West South Central, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types | 215 |
| Figure 31 | Absolute amount of LED increase attributed to each building type for select years | 216 |
| Figure 32 | For Pacific, percent of the total increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types | 218 |
| Figure 33 | Absolute amount of LED increase attributed to each building type for select years | 219 |
| Figure 34 | For New England, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories | 223 |
| Figure 35 | For New England, the share of total change in capacity attributed to each electric power capacity type | 224 |
| Figure 36 | For Mid-Atlantic, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories | 225 |

| | | |
|-----------|---|-----|
| Figure 37 | For Mid-Atlantic, the share of total change in capacity attributed to each electric power capacity type | 226 |
| Figure 38 | For West South Central, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories | 227 |
| Figure 39 | For West South Central, the share of total change in capacity attributed to each electric power capacity type | 228 |
| Figure 40 | For Pacific, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories | 229 |
| Figure 41 | For Pacific, the share of total change in capacity attributed to each electric power capacity type | 230 |
| Figure 42 | All regions' results: Percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types | 235 |
| Figure 43 | All regions' results: Percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories | 236 |
| Figure 44 | All regions' results: The share of total change in capacity attributed to each electric power capacity type | 237 |
| Figure 45 | An example of LEDs being used for horticultural lighting at frequencies that don't seem aesthetically appealing but nevertheless promote strong plant growth. Source: Mattison, 2016 | 256 |
| Figure 46 | NEMA's visualization offered in support of their claim that subsequent lighting efficiency rulemakings have had diminishing energy-efficiency returns. Source: National Academies of Sciences Engineering and Medicine, 2017 | 259 |
| Figure 47 | Between 2008 and 2015, a decline occurred in the cost-per-unit-of-illumination along with a corresponding increase in total US installations for LED commodity lamps (aka LED A-Type lamps). Source: US Department of Energy, 2016b | 267 |

SUMMARY

The studies in this dissertation – concerning inter-firm R&D collaboration, patent production and sharing, and electric power infrastructure – will illustrate the influence of path-dependency on outcomes delivered by policies stimulating innovation in the lighting sector. This dissertation will build upon prior findings in path-dependency studies by applying path-dependency to distinct policies: collaboration-enhancing policies, patent licensing requirements, and lighting subsidies paired with emissions regulations. In doing so, the studies will highlight the social factors that influence lighting innovation. Just as the dominance of the electric lightbulb was not produced from a good idea alone – needing trade cartels and patent attorneys to achieve just its initial growth – so too do contemporary ideas for changing the way we illuminate the world rely on resources far greater than new technology ideas alone. In highlighting factors that frustrate the aims of contemporary innovation policies towards lighting, this dissertation aims to inform the design of future innovation policies such that future policies may account for influential factors and design strategies that nullify or take advantage of such factors to enact change.

CHAPTER 1. INTRODUCTION

Solid-state lighting (“SSL”) is a promising new technology that policies have sought to develop in the hopes of achieving widespread lighting innovation, but such policies are at risk for having their hopes flustered by path-dependencies. SSL technology replaces filaments or fluorescent gases used in conventional lighting devices with semiconductor materials that emit light when electrified. SSL technology has several advantages over conventional lighting, including superior energy efficiency, longer useful life, and greater customizability in terms of the quality of light output. Policies have sought to develop SSL technology through direct policies, such funding of SSL R&D, but also through policies that favor R&D in general such as policies fostering R&D collaboration between firms. Policies have also pursued lighting innovation by directly subsidizing energy-efficient product adoption and generally penalizing energy-intensive devices through limits on emissions from the electric power sector. Despite the goals of such policies, however, many factors can lead to a continuation of current circumstances – new technologies can remain undeveloped and new products can remain un-adopted. Such factors can include consumers’ history with certain products, the inherent capabilities of firms performing the R&D, and infrastructure designed to support the incumbent technology. Scholars refer to these factors as “path-dependencies,” a name referring to the fact that such factors are often grounded in history. The history of the compact fluorescent bulb (CFL)’s failure to transform conventional lighting markets and the many path-dependencies that led to CFL’s failure serves as an example that path-dependencies can indeed fluster policy hopes for lighting innovation (Sandahl, Gilbride, Ledbetter, R.Steward, & Calwell, 2006).

To help lighting innovation policies avoid being flustered by path-dependencies, this dissertation seeks to provide insights where path-dependencies may arise and how to work around them. This dissertation analyzes three policy areas that have been essential to the development of SSL technology and SSL-driven lighting innovation – inter-firm R&D collaboration, patent licensing, and emissions regulation. These three areas constitute the most significant ways policy has attempted to shape the development of SSL technology and wider SSL-driven lighting innovation. In each area, the dissertation applies a path-dependency analysis seeking out latent factors that frustrate policies pursuing innovation. To do so, the dissertation starts with a literature review of studies on path-dependencies affecting R&D and energy infrastructure, the latter being relevant to emissions regulation. The dissertation then presents three chapters, each detailing a separate analysis of path-dependencies in one of the three policy areas.

1.1.1 Chapter 3: policies for inter-firm collaboration and SSL technology development

The study presented in Chapter 3 analyzes path-dependencies affecting policies that support inter-firm R&D collaboration by exploring the break-up of a SSL-R&D-focused joint venture. In the late 1990s, Philips and Hewlett-Packard (HP) created an important private sector investment in SSL technology development through the short-lived Lumileds joint venture. Lumileds sought to combine HP's optics expertise with the lightbulb product design and manufacturing knowhow of Philips. Lumileds represented the most significant private investment in SSL R&D – the joint venture stood at the cusp of a growing SSL market with a dominant market share and a long technological lead relative to competitors. Moreover, the policy environment of the late 1990s supported inter-firm R&D collaboration and encouraged the Lumileds joint-venture. Despite such a positive environment for Lumileds, however, HP abandoned the joint venture after six years and discontinued SSL product R&D. Given the importance of Lumileds to privately funded SSL

technology development and the supportive policy environment for Lumileds, Chapter 3 seeks to understand why the disruption of Lumileds happened. Chapter 3 provides a path-dependency analysis to the history of Philips, HP, and Lumileds so as to reveal specific factors behind Lumileds disruption. Chapter 3 seeks to offer lessons for policymakers by identifying factors that can disrupt inter-firm R&D collaboration and thus slow technology development.

1.1.2 Chapter 4: patent licensing policies for federally funded SSL R&D

The study presented in Chapter 4 analyzes path-dependencies in policies toward SSL patent licensing that seek to promote knowledge-sharing. The US federal government has provided most of the world's funding for SSL R&D through the US Department of Energy's Solid-state Lighting program (DOE SSL). However, the DOE SSL's funding has come with requirements that funded researchers provide patent licensing privileges to a specific set of SSL industry firms. The patent licensing privileges constitute a form of "compulsory licensing," a term for policies that require patent-holders to grant others the right to take actions that otherwise would infringe on the patent. However, scholarly evidence raises an issue of whether compulsory licensing policies can lead to the suppression of actual R&D. For example, a 2013 assessment of the DOE SSL program by the National Academies of Science, Engineering, and Medicine recommended that the DOE SSL program end its patent licensing policy on the grounds of negative impacts to SSL R&D activities. Such negative impacts could prevent SSL technology from being developed, contrary to the goals of the compulsory licensing policy. Given the importance of the DOE SSL program's patent licensing policy and the risk of negatively impacting R&D, Chapter 4 analyzes to understand what impacts the DOE SSL program's policy has had on funded researchers. Chapter 4 seeks to offer lessons for policymakers on how policies toward R&D funding and toward R&D sharing – with

patent licensing being one mechanism for R&D sharing – can be structured so as to encourage R&D sharing without discouraging R&D production.

1.1.3 Chapter 5: Climate change mitigation policies and SSL product adoption

The study presented in Chapter 5 analyzes how regional differences in response to climate policies can help or hinder the benefits of SSL adoption. A key driver of R&D for SSL light bulbs has been the hope that SSL light bulbs and other SSL lighting products will contribute to the goals of climate change mitigation policies. The superior energy efficiency of SSL products has long been connected with hoped-for reductions in greenhouse gas emissions. Frequently, however, policies for combating climate change are implemented at a nation-scale and fail to account for key differences between US regions. Policies such as the US wind production tax credit and the US solar investment tax credit, for example, have applied to the entire US despite the fact that certain regions do not enjoy much potential for taking advantage of such policies. Moreover, the differences between US regions in impacts of policies related to SSL product adoption constitutes a gap in scholarly knowledge. Where studies have paid attention to the role of efficient products, they have failed to analyze regional differences and SSL products' role in particular (M. Brown, Kim, Smith, & Southworth, 2017). Given the importance of carbon dioxide and other greenhouse gas emission reductions to the efforts to fund SSL technology development, as well as the potential for policies promoting SSL products to ignore regional differences and inefficiently allocate resources, Chapter 5 seeks to understand regional differences in the interactions between SSL adoption and climate policies. Chapter 5 seeks lessons for policymaking regarding where and how it may be most effective to stimulate SSL product adoption in the name of climate change mitigation benefits.

1.2 Contributions to academic debates

Beyond informing policymaking, the studies in this dissertation make contributions to path-dependency theory on par with contributions made by published academic journal articles and filling crucial gaps in the literature. While the important factors revealed through the path-dependency analyses presented in this dissertation have important implications for policymaking, the dissertation's studies contribute to path-dependency theory through unique applications of path-dependency to new areas. As will be shown in Chapter 2's literature review, academic literature on path-dependency contains several crucial gaps in terms of how and to what topics path-dependency analysis has been applied. Each study presented in this dissertation involves an original and novel application of path-dependency analysis and thus expands the scope of the theory. Moreover, as shown in Chapter 2's review of literature on path-dependency, published academic journal articles frequently serve the purpose of using path-dependency analysis to contribute a new factor that explains failure to innovate. Chapters 3, 4, and 5 of this dissertation perform exactly that task and thus make contributions on par with published journal articles.

Chapter 3's analysis makes contributions on par with published journal articles by expanding the domain of path-dependency theory to the new topic of joint ventures and brings novel content to the theory by focusing on entire firm histories. As written in Chapter 3, joint ventures have been a common topic of research in the management science and business history fields, but these fields have not applied the path-dependency analysis framework to exploring the causes and effects of joint ventures. The path-dependency analysis framework has only seen one application to joint ventures—a study by Pajunen & Fang (2013), which focuses on the beginnings and endings of joint ventures between Finnish and Chinese firms. However, Pajunen & Fang's study only focuses on how early events during a joint venture's history create lock-in effects that influence events later

in that joint venture's history. Pajunen & Fang's work does not examine the histories of the respective firms coming to the joint venture and does not incorporate those histories into explaining outcomes of a joint venture. This leaves a gap in the literature – an application of path-dependency that examines the whole history of firms involved in a joint venture. Chapter 3's analysis fills this gap by applying a path-dependency analysis that encompasses the whole scope of Hewlett-Packard's and Philips' respective histories. In so doing, Chapter 3 provides a contribution to path-dependency theory similar to that made by several published academic journal articles by contributing Core Capabilities as a new factor that explains the failure of joint ventures.

Chapter 4's analysis contributes new explanations to academic debate by not only exploring a novel topic but also by bringing path-dependency analysis to that topic for the first time. Chapter 4's analysis is novel without the addition of path-dependency in that Chapter 4's analysis studies a compulsory licensing policy for a specific technology. Compulsory licensing most famously occurred in WTO negotiations that require multi-national pharmaceutical corporations to grant small firms in developing nations the right to make drugs and medicines patented by the multi-nationals. Most scholarly literature on the impacts of compulsory licensing has focused on this example of compulsory licensing – most of the attention given to compulsory licensing in academic journal articles centers on the WTO negotiations. Conversely, very little attention has been paid to the effects of policies within a specific country focusing on a specific sub-domain of R&D such as SSL. As such, very little is known about what impacts these more focused policies may have. No study focuses on a technology-specific compulsory licensing policy. To this new area of research, Chapter 4 brings path-dependency theory for the first time. No prior study has used the path-dependency framework to analyse patent licensing, and so Chapter 4's analysis expands the domain of path-dependency theory to include not just patent licensing, not just

compulsory licensing, but compulsory licensing of patents in a specific technological domain. Beyond meeting the novelty of application standard, Chapter 4 also meets the standard of a published academic article on path-dependency theory by contributing Appropriability Regimes as a factor explaining failure to innovate.

Chapter 5's analysis contributes to the literature on path-dependency in energy systems via implementing a new paradigm of forward-looking path-dependency analysis. As shown in Chapter 2's review of literature on the path-dependencies in energy systems, the literature's published academic articles apply path-dependency retrospectively. All studies reviewed involve a historical examination of energy systems' evolution, taking advantage of time that has passed and revealed causes and effects. None of the studies provides a forward-looking approach that could inform policymaking *before* policies are implemented. As shown in the works by Alan Porter and others on forecasting technology pathways, however, path-dependency analysis *can indeed* be applied prospectively. The literature on path-dependency in energy systems has thus lagged the literature on R&D policy by failing to employ a forward-looking approach, leaving a large gap for future work. This is especially important given the strong path-dependencies present in energy systems – these strong path-dependencies make the need for analyses that can advise policymaking prospectively all the more immediate. While there is much potential for forward-looking applications of path-dependency in energy systems, Chapter 5's analysis helps to fill this gap. Moreover, Chapter 5 makes contributions to the literature on par with published academic journal articles. Chapter 5 contributes several counterintuitive findings that reject reasonable hypotheses (and common policymaking assumptions) about how energy systems would behave under expanded adoption of SSL.

1.3 Terminology: Distinguishing “innovation” from “technology development”

Importantly, this dissertation chooses carefully its use of the terms “innovation” and “technology development” so as to avoid performing a common conflation of activities that advance certain technological products with activities that change the way human civilization meets fundamental needs. Typically, writings on “innovation” portray an interlinkage between some technological research activity and the fulfillment of basic human needs. Such writings may have the effect (and may intend to have the effect) of convincing readers that support for technology research activity is critical to meeting basic human needs. This dissertation disavows that illusion. From human history, it is clear that any specific technological research activity is not necessarily critical to meeting human needs. To mitigate the possibility of propagating false ideas among readers, this dissertation provides definitions of innovation that separate it from technological research activities. This dissertation uses the term “innovation” to refer to a widespread societal change grounded in technology for producing common services. This work uses the term “technology development” to refer to humans working to arrange non-human objects so as to beget a new object that reproducibly provides some service.¹ As an example, a horse alone is not a technology – it is a non-human object. But arranging a horse with other non-human objects for the reproducible production of some service, e.g. combining a horse with a saddle or a buggy to provide transportation, constitutes a technology. Moreover, getting horse-and-buggies widely adopted, having roads made specifically to accommodate horse-and-buggies, and developing common social customs grounded in the horse-and-buggy such as Sunday rides constitutes *transportation innovation*. More relevant to this dissertation, a piece of dead tree trunk (a plant) is not a

¹ Authors of peer-reviewed publications use different definitions for innovation and technology, and they often don’t define either term clearly. Here, the intent is to provide a clear definition so that readers could assess how well the terms in this dissertation match what they have read elsewhere to better their own understanding.

technology. But chopping the tree trunk into smaller pieces, arranging them with other materials for combustion, and organizing all this into a pile to provide light (and heat) is a technology. And widespread adoption of fire pits, including social customs such as dancing and feasting at fire pits, constitutes innovation.

For this dissertation, the key example of widespread technology adoption and social customs grounded in that technology is the electrification of lighting. Lighting has been mostly provided by the sun and wood fires over human history, yet at the time of this writing most lighting is provided by a variety of devices all making use of electric power. The story of Thomas Edison's first electric lightbulb and subsequent worldwide electrification of lighting in the late 1800s and early 1900s is often offered as the explanation for how we got from there to here. However, Edison's invention of the filament bulb alone does not constitute innovation according to the definition used in this work. Rather, Edison's invention constitutes technology development. This work frequently contrasts "technology development" with "innovation" because many policies promise innovation through technology development and in reality primarily support technology development without looking to innovation.

Important factors influencing whether a technological development leads to innovation are revealed through analyses grounded in the Path-dependency Theoretical Framework. As mentioned above, many policies attempt to create innovation by targeting technology development. As will be demonstrated throughout this work, however, far more than technology development alone is necessary to achieve innovation. The path-dependency theoretical framework presumes that many factors hold the status quo in place, and that altering only one factor – say, changing the incumbent technology – will likely not be sufficient to create innovation.

CHAPTER 2. REVIEW OF PATH-DEPENDENCY STUDIES AND THE HISTORY OF SOLID-STATE LIGHTING R&D

2.1 Literature on path-dependencies in R&D and energy systems

In search of answers to the research questions raised in Chapter 1, this dissertation first turn to published academic literature on path-dependency and its applications to R&D and energy systems. Since the first two questions raised in chapter one concern technology development, we review the literature on applications of path-dependency to R&D activities (recall that this dissertation defines technology development to consist of most types of R&D activity). Since the third question concerns energy systems, we review the literature on applications of path-dependency to energy systems as well.

While this review of literature on path-dependency in R&D and energy systems reveals helpful insights about the general nature of path-dependency in both areas, this review also highlights critical gaps in the literature for purposes of answering the dissertation' research questions. This review outlines those gap as the motivating and justifying context for the original research to follow in the next three chapters.

2.1.1 Path-dependency and R&D in firms, regions, and sectors

Many works focus on firm-level or industry-level R&D innovation, finding local branding and re-deployment of existing institutions to be useful strategies for breaking out of R&D path-dependency. Importantly, a study by Pajunen & Fang (2013) applies path-dependency analysis to a sample of technology-focused joint ventures between Finnish and Chinese firms. Pajunen & Fang's study focuses on how early events during a joint venture's history create lock-in effects

that influence events later in that joint venture's history. Nelson & Winter (1982) provide a theoretical framework analyzing the importance of the routines and structures an R&D-intensive firm sets out at the beginning of its existence in determining the later responses of the firm to changes in the firm's business environment. Analyzing knowledge-management practices within firms, Coombs & Hull (1998) find that some practices do more than others to enable firms to innovate and break out of path-dependency. As an example, Aylward (2006) argues that adapting innovation activities to local concerns, such adapting the Australian wine industry's centralized R&D governance to needs for regional branding of wine products, can disrupt path-dependency and restore innovative activity. Moreover, Strambach (2008) finds that firms can innovate even in the face path-dependency, for example in the face of institutional environments favoring an incumbent technology. Using the coined term "Path Plasticity," Strambach argues that agents can re-deploy established institutions away from incumbent technologies and toward innovative ends. In studying the lighting industry's diverse portfolio of products, Onufrey & Bergek (2015) elaborate that some self-reinforcing activities can also reinforce other activities, while other self-reinforcing activities can inhibit other activities. The former can lead to situations in which multiple self-reinforcing activities exist – i.e. a multi-path scenario – while the latter leads in general to a single self-reinforcing activity.

Taking reinforcing patterns and scenarios to the regional level, path-dependency analyses also commonly focus on innovations in regional policies toward R&D, finding integrating and cross-boundary collaboration activities as helpful means for breaking out of path-dependency. In the case of regional innovation, Cooke (2005) argues that breaking out of a region's economic path-dependency requires integrating the regions innovation and education systems, which among other things benefits technology transfer within the region itself. In a similar manner, Pylak (2015) notes

several internal factors that contribute to the propensity of an entity to break out of a path-dependency in the context of regional economic growth. Pylak finds in general that high level of knowledge and competency enables regions to break out of path-dependency more often than regions with lower knowledge and competency levels. Examining the regional innovation system of Germany's Baden-Wuttemberg province as a specific example, Baier, Kroll, Schricke, & Stahlecker (2012) find that routinized innovation activity structures do not by necessity promote path-dependency because they do not by necessity inhibit exploration of novel technology areas. Moreover, Baier et al. find that having a diverse set of core economic and technical competencies mitigates path-dependency by helping entities adapt to external changes, such as sweeping technological change. Finally, In analyzing the success of Finland's national innovation system and economic growth, Park & Lee (2005) notes that Finnish government's proactive approach to fostering cross boundary collaboration and facilitating R&D planning efforts across sectors enabled the country to liberate its R&D from a path-dependency created by historic trade ties with the Soviet Union.

Path-dependency's application to R&D has not only been retrospective – applications of the path-dependency theory can also have prospective, i.e. forward-looking, components as well. The practice of looking forward at pathways for technological development has been well-established through the works of Alan Porter and other scholars. Porter's work highlights the prospective usefulness of the Path-dependency Framework for producing reasoned expectations and plans for action regarding how to shape the future development of a technology. The work of Porter and others (Cunningham & Porter, 2011; Kwon, Porter, & Youtie, 2016; Lahoti, Porter, Zhang, Youtie, & Wang, 2018; Porter & Cunningham, 2005; Youtie et al., 2012) focuses in part on using (1) intensive, retrospective data analysis on what paths a technology's development has taken, and (2)

intensive, prospective discussions with experts in order to establish what paths a technology's development might take in the future (Huang, Guo, Porter, Youtie, & Robinson, 2012). In both the retrospective and prospective analysis, Porter's approach seeks to identify the interdependencies between a technology and related (or adjacent, but not yet related) areas of scientific research, related (or adjacent) areas of commercial activity, and other factors outside of the development of the technology itself that may influence a technology's trajectory. Identifying the interdependencies becomes important in the context of what Porter and others refer to as "NESTs" - New & Emerging Science & Technologies. While prior technology forecasting efforts focused on innovation pathways that were more linear in nature owing to the military application of the technologies-of-interest, NESTs are subject to a greater variety and number of influences and experience non-linear innovation pathways. In addition, NESTs are expected to generate significant wealth for those able to anticipate and take appropriate positions on NESTs' development pathways (Porter, Guo, Huang, & Robinson, 2010). An example of the type of analysis that Porter's approach has produced for dye-sensitized solar cells appears in Figure 1, showing how the Path-dependency framework can be applied to forecasting in the form of a multi-path map showing options for long-term technological development. The multi-path map concept illustrated here enters Porter's work through prior work of Robinson & Propp (2008).

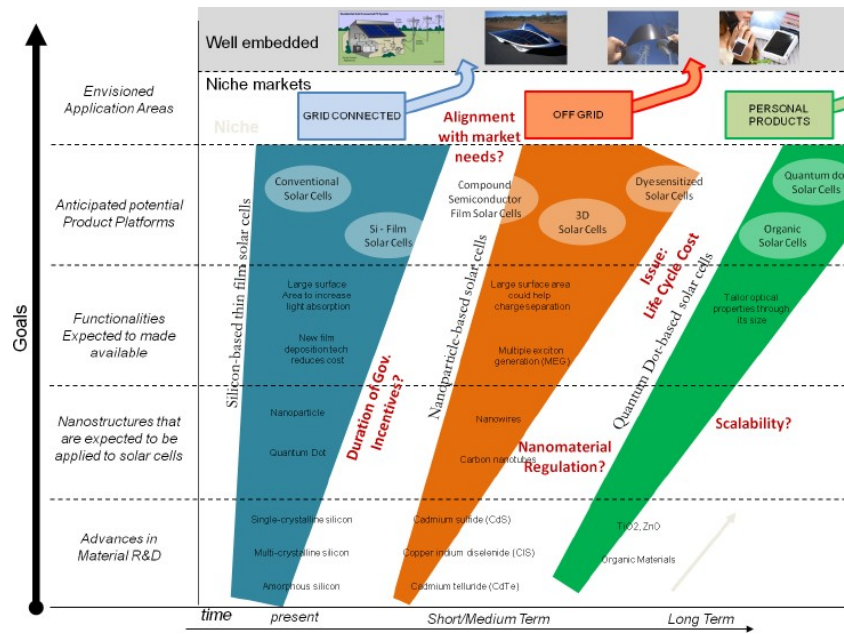


Figure 1: A hypothetical technology multi-path map for dye-sensitized solar cells, showing an example of how the Path-dependency Framework can be applied to forecasting. Source: (Porter et al., 2010)

2.1.2 Path-dependency and energy systems

Prior research finds the energy sector prone to path-dependency's influence. Buhanist (2015) finds that Groningen-style contracts for gas imports continue to persist after the global recession that began in 2008-2009 decreased gas demand and caused severe financial harm to the contracts' buyers. Buhanist attributes the persistence of Groningen-style contracts to path-dependency, for while the global recession demonstrated a tremendous need for innovation in gas import contract design, no such innovation occurred in the following six years. Seeking to explain this inertia, Wolsink (2012) argues that the centralized regulation and technological design creates inherent path-dependency in energy infrastructure. Moreover, Palm (2006) finds that the representation of

local energy companies across a greater number of policy-making situations than other interests like environmental advocates, who were represented in far fewer policy-making situations, served to enable path-dependency in the energy policy of two Swedish municipalities. Fagerberg, Mowery, & Verspagen (2009) find that, in Norway, an energy-focused economic development strategy created its own path-dependency, limiting innovative efforts to grow industries unrelated to energy. Gjelsvik & Aarstad (2017) affirm this finding, highlighting the role of the financial sector in Southwest Norway for continuing to invest in energy-dependent industries even in periods of abundant capital. National Bureau of Economic Research (2012) also finds strong evidence for path-dependency in energy sector innovation, such as firms that have innovated in both fossil-intensive and clean energy technologies previously being likely to continue doing so regardless of incentives to change.

Clean energy technologies are frequently used to illustrate the degree to which path-dependency is endemic to the energy industry across the world, and this has been called out by important practitioners seeking to influence global policy designs. For example, in calling for economic growth strategies powered by clean energy and other sustainable practices, the Organization for Economic Cooperation and Development (2012) emphasizes a great deal of path-dependency opposing transition efforts: “Changing current patterns of growth, consumer habits, technology, and infrastructure is a long-term project, and we will have to live with the consequences of past decisions for a long time. This ‘path-dependency’ is likely to intensify systemic environmental risks even if we were to get policy settings right relatively swiftly.” (Organization for Economic Cooperation and Development, 2012, pp.3) The Organization for Economic Cooperation and Development calls for temporary government support of innovative energy technologies as a

means for breaking out of path-dependency, but cautions against policies that may by design create their own path-dependencies and stifle further innovation.

Beyond avoiding path-dependencies created by policies themselves, policy design in general is sometimes a weak point for path-dependency analyses that frequently focus on characterizing the path-dependency inherent in the energy industry. Nonetheless, the application of path-dependency framework still has yielded some useful insights – both in highlighting naïve policy making that should consider path-dependencies with greater care, and also in highlighting means of breaking free of energy sector path-dependencies. Looking forward, Scholvin (2014) applies path-dependency theory to evaluate options for the future of South Africa’s capacity-constrained and coal-dominated electric power industry. Scholvin highlights that the most prevalent options at the time failed to account for many relevant conditions owed to history of South Africa’s electric power industry. Kivimaa & Virkamäki (2013) use an economic development path-dependency to explain policy development processes in Finland and the UK focusing on transportation energy technology innovation that focuses on private automobiles, highlighting that alternative innovation pathways for reducing transportation demand should account for these path-dependencies. Emphasizing means of breaking free of path-dependencies, Essletzbichler (2012) notes that localized processes aid implementation of national efforts to achieve energy transition and break out of path-dependency. On a similar note, Becker, Beveridge, & Rohring (2016), in addressing the German city of Hamburg’s referendum on whether to place certain electrical networks under ownership and control of the city’s government, argues that a efforts to break free of path-dependency can be augmented by external environmental changes – such as a wider rebirth of interest and demand for public ownership in general.

2.1.3 Gaps identified in the path-dependency literature

As shown in the literature review, the domain of path-dependency theory has very little analysis of joint ventures and entire firm histories. While joint ventures have been a common topic of research in the management science and business history fields, these fields have not applied the path-dependency analysis framework to exploring the causes and effects of joint ventures. The path-dependency analysis framework has only seen one application to joint ventures – the study by Pajunen & Fang (2013), which focuses on the beginnings and endings of joint ventures between Finnish and Chinese firms. However, Pajunen & Fang’s study only focuses on how early events during a joint venture’s history create lock-in effects that influence events later in that joint venture’s history. Pajunen & Fang’s work does not examine the histories of the respective firms coming to the joint venture and does not incorporate those histories into explaining outcomes of a joint venture. This leaves a gap in the literature – an application of path-dependency that examines the whole history of firms involved in a joint venture.

Another gap in the literature is that path-dependency theory also has yet to be applied to patent licensing policies, let alone compulsory licensing policies for a specific technology like the DOE SSL program’s patent licensing privileges. From the literature review, it is clear that path-dependency theory has not yet been applied to the topic. No prior study has used the path-dependency framework to analyse patent licensing, let alone a technology-specific compulsory licensing policy like the US DOE SSL program’s patent licensing privileges. Path-dependency theory has yet to be applied to patent licensing, compulsory patent licensing, and compulsory licensing of patents in a specific technological domain like SSL.

Beyond gaps in the technological domains and other areas of application, academic literature on path-dependencies in energy systems lacks strength in the domain of forward-looking path-dependency analysis. Most of the literature's published academic articles apply path-dependency retrospectively, with the exception of Scholvin (Scholvin, 2014) who's study only analyzes the energy system of South Africa and thus lacks insights for the US energy system. The published articles frequently involve a historical examination of energy systems' evolution, taking advantage of time that has passed and revealed causes and effects. None of the studies provides a forward-looking approach that could inform policymaking *before* policies are implemented. As shown in the works by Alan Porter and others on forecasting technology pathways (Huang et al., 2012), however, path-dependency analysis *can indeed* be applied prospectively. The literature on path-dependency in energy systems has thus lagged the literature on path-dependency R&D policy by failing to employ a forward-looking approach, leaving a large gap for future work. This is especially important given the strong path-dependencies present in energy systems identified by the literature, because these strong path-dependencies make the need for analyses that can advise policymaking prospectively all the more immediate.

Given the need for analyses advising policymaking and the gaps in the literature identified in this review, it is clear that new work is needed to both address the questions and fill in the gaps. The following three chapters each describe original research undertaken to address one of the dissertation's research questions.

2.2 A brief history of SSL R&D

2.2.1 1940s through 1970s: Solid-state lighting occupies small niche applications

Contrary to SSL R&D's focus nowadays on efficient lightbulbs, early SSL R&D was rather conservative in nature and focused on basic materials and applications in other industries highly dependent upon semiconductors. The development of SSL from the 1940s through the 1970s followed patterns exhibited by other fields of technology. Large US firms performed most of the world's SSL R&D and produced most of the SSL products. Firms did not collaborate, had little R&D background of their own to build from, and experienced slow and sporadic progress. Researchers found SSL technology applications that largely supported other emerging and semiconductor-intensive fields, such as computing.

While conducting R&D on LED materials in support of other semiconductor applications, US firms also sought potential sales revenues from niche applications for the earliest LED technologies. Pursuit of a diverse set of R&D paths by a diverse set of firms yielded steady improvement in LED performance and enabled a succession of LED niche applications. During the period between World War II and 1980, LEDs achieved new applications and competed with existing lighting technologies in indicator lighting, such as calculator displays and watches.

As with their performance of LED R&D for indicator lighting applications, major US firms led the way in finding niche applications for LED products. IBM used LEDs as indicator lights to signal data processing on its mainframe computers. Texas instruments developed indicator LEDs for controls on its audio and video equipment and local area communicators. Many large US firms pursued the integration of LEDs into calculators and digital displays as those technologies

themselves emerged in the 1960s and 1970s (Haitz, Kish, Tsao, & Nelson, 2000). Table 1 shows some examples of niche LED applications that US firms negotiated between 1960 and 1970.

Table 1: Examples of LED niche applications between 1960 and 1970. Source: Sanderson & Simons, 2014

| <i>Year Introduced</i> | <i>Application</i> | <i>Pioneer firm</i> |
|------------------------|--------------------------------|--------------------------|
| 1962 | Circuit board indicator lights | Texas Instruments |
| 1962 | Alpha-numeric displays | General Electric |
| 1967 | Indicator lights | Monsanto/Hewlett-Packard |
| 1968 | Early electronic display | Hewlett-Packard |
| 1970 | LED watch | Hamilton Watch Company |

2.2.1.1 1945 to 1979: The performers of the world's solid-state lighting R&D

Originating in the post-World-War-II work by US firms on semiconductors, a variety of US firms performed much of the world's R&D on the earliest SSL technology. Multiple US firms pursued R&D on Light-emitting Diodes ("LEDs") in desire of both scientific knowledge and commercial productivity. Initial progress in LED technology was quite slow. Researchers at US firms used one another's discoveries to propel further R&D, but the researchers frequently stopped and re-started their LED work. Most frequently, researchers would initiate a new LED R&D path by trying to synthesize a new light-emitting semiconductor material; researchers at US firms created several new materials in pursuit of promising LED R&D paths. Little clear idea of what types of LED R&D would be most productive existed in the 1950s and 1960, however, and researchers found themselves pursuing initially promising LED R&D paths that ultimately led to no resolution. Conversely, as later history would show, certain R&D paths that did not initially seem promising turned out to be quite fruitful. The lack of formal inter-firm collaboration on LED likely hampered

technological progress, since the individual firms each had relatively little progress of their own and were already trying awkwardly to build from one other's R&D.

Table 2 shows that large US firms held the wide majority of positions among the list of top-cited publications by firm between 1945 and 1981.

Table 2: Between 1945 and 1981, the top ten R&D organizations ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014

| <i>Institution</i> | <i>Country</i> | <i>Raw citations</i> | <i>Raw papers</i> |
|---------------------------------|-----------------------|-----------------------------|--------------------------|
| Bell Labs | US | 3226 | 131 |
| RCA Corporation | US | 1425 | 76 |
| IBM | US | 1277 | 58 |
| General Electric | US | 879 | 32 |
| Westinghouse | US | 859 | 59 |
| GTE Sylvania | US | 513 | 35 |
| Monsanto | US | 428 | 13 |
| Fujitsu | Japan | 310 | 13 |
| Univ. Illinois Urbana-Champaign | US | 265 | 4 |
| Kyoto University | Japan | 264 | 15 |

Early LED research centered on materials that emitted red and orange light. US firms performed intensive R&D with group III, IV, and V semiconductor compounds in the early 1950s in hopes of developing better transistors. Coincidentally, the same semiconductor compounds proved to be efficient emitters of light. Theories of the transistor gave researchers inspiration as to how semiconductor compounds might also work for LEDs (Holonyak Jr, 2013). By the 1960s, several US firms including RCA, General Electric, and IBM were researching low-energy infrared LEDs based on a particular group III/group V semiconductor compound – Gallium Arsenide (GaAs). IBM researchers pursued an aluminum-gallium-arsenide compound (AlGaAs) for LEDs, while General Electric researchers pursued LEDs based on gallium-arsenide-phosphide (GaAsP).

General Electric's Nick Holonyak saw potential for orange-emitting LEDs to replace orange-emitting, filament-based nixie tubes in alphanumeric display devices. Unfortunately for Holonyak's vision, however, the early red and orange LEDs suffered from rapid material degradation and subsequent loss in light output (Sanderson & Simons, 2014).

Despite the degradation and output losses challenges, General Electric took the lead as the first firm to sell LEDs by offering small batches of LEDs for sale in the early 1960s. Despite General Electric's first-mover advantage, however, Monsanto Corporation developed the first mass production process for LED materials and set up a factory for producing GaAsP in 1968. That same year, Monsanto introduced the first LED indicator lamps and Hewlett-Packard introduced the first truly electronic display based upon LED materials, intended as a successor to the Nixie tube (Haitz et al., 2000). Monsanto and Hewlett-Packard entered into an agreement to have Hewlett-Packard produce LED devices from Monsanto's GaAsP materials, but Hewlett-Packard soon broke the agreement and began producing its own GaAsP materials (Sanderson & Simons, 2014).

While Hewlett-Packard was going rogue on its agreement with Monsanto, AT&T's Bell Labs set a new record for LED efficiency by doping gallium-phosphide materials (GaP) with nitrogen and found quick innovations in manufacturing processes for producing GaP, helping GaP to become a dominant material for both red and green LEDs throughout the 1960s and 1970s. AT&T built upon its own success with GaP for red LEDs by developing GaP for green LEDs. Despite having low brightness, AT&T's green LEDs inspired researchers in the US to pursue a greater range of LED colors. In particular, AT&T's green LEDs inspired RCA researchers Paul Tietjen and Jacques Pankove to each separately pursue blue LEDs in the early 1970s. Tietjen worked with Stanford PhD student Paul Maruska to develop GaN single-crystal films, while Pankove's team developed

metal-insulator semiconductor materials (“MIS”) with GaN. Neither path yielded an efficient blue-emitting LED device, however, and in 1974 RCA ended all blue LED research. RCA’s decision to end blue LED research signaled other firms to stop research on GaN materials, and it wasn’t until the late 1980s that Japanese firms resumed pursuit of blue LEDs through GaN (Sanderson & Simons, 2014).

2.2.2 1980 to 2000: New applications for solid-state lighting and the foundations of white LEDs

In parallel with the disruptive climate policy changes from the 1980s to 2000, SSL experienced disruptive technological change. Improvements in materials for orange and red LEDs made them popular for new niche applications in the 1980s and 1990s. New regulations required automobiles to have a center high-mount stoplight (CHMS) installed. Because of significant expected cost advantages to high-brightness and low-lamp-count LED device for the CHMS application, many researchers began pursuing new materials for red LEDs. By 1990, researchers had developed a device based on aluminum-gallium-arsenic (AlGaAs) material with 10 lumens-per-watt efficiency – enough to rival and exceed the efficiency of a red-filtered incandescent lamp (the incumbent device of the time). The AlGaAs-based devices had limited color spectrum, however – able to emit only a deep red that worked well for automobile signaling but not much else (Haitz et al., 2000). An aluminum-gallium-indium-phosphide (AlInGaP) material developed soon after the AlGaAs devices enhanced efficiencies and enabled between 10 and 20 lumens-per-watt efficiencies for a wider color spectrum of orange and red LEDs. The new levels of brightness from AlInGaP-based LEDs made them an attractive option for automobile taillights and for traffic signals (Johnstone, 2007). The late 1980s and early 1990s also witnessed the resurgence of the gallium-nitride (GaN) material. Originally abandoned in the mid-1970s when RCA ceased GaN research due to low overall operations income, the new environment of global R&D competition saw Japanese

researchers taking up the quest for the blue LED in the late 1980s. Researchers resolved GaN p-doping difficulties by 1991, setting the stage for the first high-output, high-efficiency blue LED device that would inspire a new wave of efforts toward developing a white LED for general illumination (Sanderson & Simons, 2014).

Meanwhile, the foundation for white light LEDs was being laid in the form of Japanese research that finally unlocked the keystone to white LED light - a high-emitting blue LED. Two Japanese researchers – Isamu Akasaki of Nagoya University and Shuji Nakamura of Nichia Chemical Industries – separately developed processes for p-doping GaN LED devices to make them blue LEDs. Akasaki found in 1986 that a low-power electron beam could activate a key impurity for GaN p-doping: magnesium (Amano, Sawaki, Akasaki, & Toyoda, 1986). Separately and later, Nakamura began working with GaN and indium-gallium-nitride (InGaN) materials, each of which had been dismissed by earlier LED researchers because of known frequency of defects in these materials' crystals. Nakamura knew that the common process for annealing GaN materials used ammonia during the cooling process; during cooling, however, the ammonia decomposes and releases atomic hydrogen. The atomic hydrogen would then de-activate the p-doping of the GaN material. The phenomenon, called “Hydrogen Passivation,” was well-known to researchers who had worked with other materials for LEDs decades earlier. Because of the non-collaborative nature of US-firm-dominated R&D between World War II and 1980, however, the knowledge never reached GaN researchers until Nakamura's work. Instead of using ammonia, Nakamura annealed his materials in pure nitrogen gas, avoided Hydrogen Passivation, and retained a p-doped GaN material (Nakamura, 1991). Nakamura's process proved to be the first such process for reliably growing GaN-based materials for blue LEDs, and moreover the materials enabled blue LED devices 200-fold brighter than prior blue and green devices. In 1992 Nichia demonstrated

unprecedented efficiencies for both blue and green LED devices based on Nakamura's InGaN materials. Nakamura's materials also enabled new blue-laser devices, enabling a new wave of applications such as blu-ray discs and DVD-ROMs.² Most consequentially, Nichia and other industry leaders saw Nakamura's high efficiency blue LEDs as the key stepping stone toward developing LED devices for producing white light (Haitz et al., 2000). Not only could blue LEDs be color-mixed with red and green LEDs to produce white light, but the high-energy light from blue LEDs could be converted to lower-energy red and green light via transmission through phosphor materials – a process called “Down Conversion.” Nichia took advantage of its expertise with phosphor materials for television displays and developed devices that Down Converted light from Nakamura's blue LEDs into a controllable mixture of colors, including white light. Nichia released the world's first white LED in 1996. The device used a yellow yttrium-aluminum-garnet (YAG) phosphor to cover the blue LED and thus down-convert blue light into white light (Johnstone, 2007).

After acquiring blue light LED technology, however, Nichia pursued a very aggressive technological and legal strategy to capitalize on the new discovery. Unlike the strategy Nichia had followed with prior products, Nichia chose not to license its blue LED technology after its demonstrating in 1993 and instead chose to invest in facilities for LED production. Nichia saw itself as having a first-mover advantage and wanted to capitalize on the opportunity to build exclusive competency in a technology widely demanded. Moreover, Nichia's choice precipitated huge growth in sales of new mobile phones with displays requiring white LED backlights, and the subsequent demand for white LEDs from mobile phone suppliers created huge sales and high

² The short wavelength of blue laser light enables more dense storage of digital memory in devices such as DVDs and CDs.

profits for Nichia (Kishi & Takahshi, 2010). Nichia's success did not rely solely on its blue LED technology, however, and instead came about from an aggressive legal strategy that Nichia used to keep other firms from producing blue LEDs. After acquiring several patents, Nichia sued firms such as Japan's Toyoda-Gosei and the United States' CREE who were trying to produce their own blue LEDs based on R&D and processes distinct from Nichia's. A long series of appeals, countersuits, and settlements followed and lasted for many years. While Nichia's legal action gave it some early advantages, court decisions in 2002 eroded those advantages by forcing Nichia to sign cross-licensing agreements with Toyoda-Gosei and CREE. Cross-licensing agreements amounted to technology-sharing between the battling firms. The legal battles influenced Nichia's strategy, and the firm began to instead actively pursue cross-licensing agreements – signing two such agreements in 2002, one with Lumileds and another with Osram-Sylvania (Sanderson & Simons, 2014). Table 3 shows new applications for LEDs that emerged between 1980 and 2010, as well as the firms that pioneered each application.

Table 3: From 1981 to 2010, new applications for LED technologies and the firms that pioneered each application. Source: Sanderson & Simons, 2014

| <i>Introduced</i> | <i>Application</i> | <i>Pioneer</i> |
|-------------------|--|---|
| 1981 | Early LED traffic lights | Electro-Tech's |
| 1980s-1990s | Auto interior lighting, early color LED displays | Siemens, Sanyo, and later CREE |
| 1993 | Bright blue LED, enabling electronic device backlighting | Nichia, Toyoda Gosei |
| 1990s | Bright white LEDs; LED streetlights, flashlights, traffic lights | Nichia, Lumileds, CREE |
| 1997 | Architectural lighting | Color Kinetics |
| 2000s | LED light bulbs | Various firms |
| 2004 | Commercial LED daylight auto headlamp | Audi, Lumileds |
| 2004 | AC LED (low power) | Industrial Technology Research Institute (Taiwan) |
| 2007 | OLED Television | Sony |

2.2.2.1 1980 to 2000: Changes in the performers of the world's solid-state lighting R&D

Along with other technology-based industries, lightbulb manufacturing had become a globally competitive industry during and after the 1980s. As of the early 2000s, multinational European firms like Philips and Osram-Sylvania and the Japanese conglomerate firm Toshiba dominated lightbulb manufacturing. Among US firms, only General Electric held much presence in the lightbulb manufacturing market. Moreover, even the four giants mentioned here saw their market shares slowly eroding due to competition from manufacturers in China and other developing nations (Sanderson & Simons, 2014).

Coinciding with competition from China and the developing world was the decision by several large US firms to abandon their SSL endeavors. Monsanto sold its LED R&D activities to a firm eventually acquired by Taiwanese firm Everlight Electronics, an LED manufacturer. One of Monsanto's leading researchers, George Craford, acquired a new position leading Hewlett-Packard's LED R&D. Hewlett-Packard continued LED R&D for many applications and with the ultimate hope of developing LEDs for general white-light illumination. Another Hewlett-Packard researcher, Roland Haitz, founded a joint-venture with Philips called "Lumileds Lighting" specifically intended to develop LEDs for general purpose lighting (QuarkStar Inc., 2015). In 1999, however, Hewlett-Packard spun off Agilent Corporation and transferred the LED R&D and the new Lumileds Lighting joint venture to Agilent. After some financial difficulties, however, Agilent sold its stake in the joint-venture to Philips in 2005 and thus ended the Hewlett-Packard line of R&D into LEDs (House & Price, 2009). Table 4 shows the top-ranked organizations by citations to papers published on LED technology between 1982 and 1991. In comparison to Table

1, a change from dominance of large US firms to strong international competition becomes quite apparent, with many of Table 4's rows being occupied by Japanese firms and other spots being occupied by firms of other non-US origins.

Table 4: Between 1982 and 1991, the top ten R&D organizations ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014

| <i>Institution</i> | <i>Country</i> | <i>Raw citations</i> | <i>Raw papers</i> |
|---|-----------------------|-----------------------------|--------------------------|
| Osaka University | Japan | 1562 | 24 |
| Fraunhofer Institute of Applied Solid-state Physics | Germany | 829 | 3 |
| AT&T Bell Labs | US | 598 | 41 |
| Nichia Corporation | Japan | 430 | 1 |
| MIT | US | 403 | 7 |
| NTT Corporation | Japan | 354 | 34 |
| University of Joseph Fourier | France | 349 | 1 |
| University of Texas at Austin | US | 346 | 9 |
| University of Toronto | Canada | 325 | 2 |
| North Carolina State University | US | 323 | 3 |

The 1990s would see a resurgence of US presence in SSL R&D, but not necessarily the resurgence of large US firms. Table 5 shows the top-ranked organizations by citations to papers published on LED technology between 1992 and 2001. While US organizations occupy many of Table 5's rows, five out of the seven US organizations are universities. Only two US large firms make the list – Xerox and Bell Labs, which had long been separated from AT&T. Table 5 exemplifies the rise of universities as global R&D competitors.

Table 5: Between 1992 and 2001, the top ten firms ranked by citations and papers published on the topic of inorganic LEDs. Source: Sanderson & Simons, 2014

| <i>Institution</i> | <i>Country</i> | <i>Raw citations</i> | <i>Raw papers</i> |
|---|-----------------------|-----------------------------|--------------------------|
| Nichia Corporation | Japan | 7589 | 71 |
| University of Illinois Urbana-Champaign | US | 6565 | 66 |
| Bell Labs | US | 4631 | 72 |
| MIT | US | 4583 | 69 |
| University of California Santa Barbara | US | 4058 | 58 |
| University of California Berkeley | US | 3959 | 36 |
| Harvard University | US | 3186 | 15 |
| Tohoku University | Japan | 3042 | 61 |
| Xerox Corporation | US | 2516 | 33 |
| University of Cambridge | UK | 2257 | 48 |

2.2.3 Policy and Technology converge: Emissions reduction policies create new opportunity for solid-state lighting technologies

Policy-driven demands for reducing greenhouse gas emissions enabled a new application for SSL – that of high-efficiency general illumination. Semiconductor and optics researchers did not fail to grasp the energy-efficiency value of SSL in the new emissions-reduction-focused policy environment. Researchers from multiple sectors began touting the value of SSL as no longer a durable, long-lived technology – but also one of high energy efficiency and thus capable of enabling reductions in greenhouse gas emissions. This section describes a proposal exemplifying the shift in perception among SSL researchers of how their technology would be valued and how the technology ought to be marketed to investors.

A key example of the shift in perception around marketing’s value case for SSL technology, and an example crucial to the history of the DOE’s SSL program, appears in the original proposal for a federally funded R&D program put forth by Haitz, Kish, Tsao, and Nelson in the year 2000. The

proposal laid the foundation for the eventual creation of a DOE SSL program in the Energy Policy Act of 2005, and the proposal is widely credited as the origins of today's program (QuarkStar Inc., 2015). The proposal makes numerous references to the carbon-dioxide-reducing potential of SSL, reflecting the new perceived value of SSL's energy-efficiency advantages in the greenhouse-gas-reducing policy environment.

Emphasis on the greenhouse-gas-reducing policy environment was critical because, despite the energy-efficiency advantages of SSL technology, few private firms were investing seriously in the technology. The financial situation of major lighting manufacturers motivated the Haitz et al. proposal. Roland Haitz – the first author of the proposal and a leading semiconductor and optics researcher at Hewlett-Packard for decades – believed strongly in the potential of SSL to replace filament bulbs and fluorescent tubes for general illumination. Yet Haitz saw SSL R&D to be too expensive an undertaking for incumbent lighting manufacturers – namely General Electric, Philips, and Osram Sylvania – to find it worth putting up capital and investing in SSL R&D. Global competition in lighting products had whittled prices down so low as to create razor-thin margins for lighting product manufacturers. Any money spent on R&D would have appeared in the near term to be “burning cash” – throwing money away completely on a futile investment. Haitz saw a crucial gap created by what he believed to be the relatively long break-even time for any investment in SSL R&D. Federal funding could fill this gap, however, according to Haitz's view (QuarkStar Inc., 2015).

In pursuit of the federal funding needed to fill the gap in SSL investment, Haitz recruited colleagues at Hewlett-Packard and at Sandia National Laboratories (QuarkStar Inc., 2015). Together they drafted a proposal for a federally funded R&D program focused on SSL in the name of – importantly – energy savings. Since the immediate benefits of SSL R&D funding were likely

to accrue first to researchers and secondly to firms deploying any newly arisen technologies, Haitz et al. needed a social benefits premise to justify the proposal. Haitz et al. certainly did find a story, but one that differed from the story they would have told if they had made their proposal during the early years of SSL R&D. For rather than focusing on durability (e.g. military/aerospace and "national security" applications), lifespan (e.g. consumer savings in avoided replacements), or even color-control values created by SSL, Haitz et al. focused their proposal upon SSL's energy-saving value. In the policy environment of the proposal, which Haitz presented in Washington D.C. in 1999 (QuarkStar Inc., 2015), energy consumption had become synonymous with greenhouse gas emissions.³ Moreover the new policy goal of reducing greenhouse gas emissions had just emerged, notably with the then-recent Kyoto Protocol agreement. The new policy goal placed re-framed energy-consuming technologies as having value to the extent that they could reduce energy consumption itself and, by extension, reduce greenhouse gas emissions. Haitz et al. saw the opportunity to bolster their proposal for R&D funding and included several features in their proposal to make apparent SSL's energy-saving potential.

To make apparent the energy-saving potential, and serving as evidence of the perception-shift regarding the value of SSL, Haitz et al.'s proposal makes many statements arguing that SSL can enable significant reductions in both energy consumption and associated greenhouse gas emissions. Early in the proposal, Haitz et al. make as context a direct reference to the Kyoto Protocol and the United States' agreement to reduce greenhouse gas emissions:

³To those willing to admit consensus science into their conscience

“In the Kyoto Protocol of 1997, e.g., the developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The United States agreed to reduce emissions from 1990 levels by 7% during the period 2008 to 2012.” (Haitz et al., 2000)

Haitz et al. go on to claim that white-light SSL products for general illumination would “change the way we live and the way we consume energy.” The proposal claims that by the year 2025, and in every year following, the amount of electricity consumed by lighting would be cut in half by envisioned SSL technologies. Specifically, the proposal estimates a potential savings of more than 1,000 tera-watts of electricity per year. In addition, the proposal estimates that the avoided energy consumption in 2025 and thereafter would also avoid approximately 220 million tons of carbon emissions per year (Haitz et al., 2000).

While the proposal and its references to potential avoided carbon emissions did not immediately beget federal investment, Haitz et al.’s 2000 proposal foreshadows the DOE SSL program created in 2005. The proposal foreshadows such details of the DOE SSL program as the program’s annual budget amount, the program’s essential industry-government partnership, and the program’s intellectual property arrangements (Haitz et al., 2000). Ironically, the proposal argues that the lighting industry would not be willing to invest in SSL without the federal funding suggested (Haitz et al., 2000); yet at the same time as the proposal’s drafting and presentation, Roland Haitz himself was leading a joint venture, called “Lumileds Lighting,” between Hewlett-Packard and Philips that would focus exclusively on SSL R&D. Moreover, it seems that, in the intervening years between the 2000 proposal and the 2005 creation of the DOE program, the lighting industry was able to sufficiently maintain investment SSL R&D to be able to absorb and make use of, if not perform, the R&D from the program’s grant-funded projects.

2.2.4 *The DOE SSL program*

The DOE SSL was created by the US Department of Energy in 2005 as a separate program under the Department's Building Technologies Office. Despite its small size, the scope and breadth of the DOE SSL program's activities are impressive. The DOE SSL program represents a huge amount of activity including government, non-profit, investor-owned, and other private actors in the name of advancing SSL technologies. The DOE SSL program funds, carries out, and coordinates efforts across multiple domains, including basic research funding, product testing, and collaborative technology pathway mapping with major industry actors. The DOE SSL program's efforts stretch across SSL products, including both LEDs and the less ready for commercialization Organic LEDs (OLEDs) whose semiconductor components are made out of organic compounds (i.e. polymers or plastics). Each year, the DOE SSL program produces a comprehensive strategy for supporting SSL R&D, through direct funding of projects as well as other activities such as convening stakeholder workshops and technology demonstration events. The DOE SSL program's annual strategy documents include both a plan for supporting R&D – the “Multi-year Program Plan” – and a roadmap for supporting SSL manufacturing activities – the “Manufacturing Roadmap.”⁴ Both are multi-year look-ahead documents designed to outline future paths for SSL technology development, and both are developed through extensive roundtable discussions with experts. As such, the DOE SSL program's guiding strategic plans are driven by SSL industry

⁴ Beginning in 2008, the Multi-year Program Plan and the Manufacturing Roadmap were formally separate documents produced through separate processes. In 2016, however, the DOE SSL program consolidated the two documents into a single annual strategic plan.

member viewpoints on key areas for R&D (Office of Energy Efficiency and Renewable Energy, 2016).

Through the program's funding of key R&D areas guided by SSL industry members and other industry support activities, the program has stimulated rapid improvements in SSL technology and has found a distinctive niche as an information broker in the lighting market. The program's intensive product testing through its CALIPER and GATEWAY initiatives provide the best source of information on the performance of new SSL products. The improvements to SSL technology have come along multiple dimensions of the technology, including color-performance, cost, energy-efficiency, lifetime, and more. Many of these improvements have come about as a result of DOE SSL research projects funded via cost-sharing agreements with privately owned industry actors. Concomitant with the National Academies' observations regarding the emergence of lighting systems sub-sector (National Academies of Sciences Engineering and Medicine, 2017), the DOE SSL program has kept pace by discussing, evaluating, and supporting R&D into SSL lighting systems (Office of Energy Efficiency and Renewable Energy, 2017).

2.2.5 Current excitement around SSL's potential for driving innovation rests primarily on technology

Since the invention of the electric lightbulb, the technology has not changed very much until recent developments in the use of semiconductors for lighting birthed the new categories of research, technology, and consumer products known as SSL. Beginning with a few key applications in the 1960s (many years after the invention of the solid-state semiconductor), SSL R&D went dormant in the late 1970s and 1980s until a major breakthrough by Japanese researchers enabled light-

emitting diodes (LEDs) to produce white light.⁵ Whereas SSL had been applied to niche applications such as indicator and signaling lights, the white LED breakthrough excited possibilities for using LEDs in general illumination. But this excitement juxtaposed very different technologies; SSL did not exist as a new refinement or incremental development in the history of incandescent bulbs or even fluorescent bulbs, and instead SSL's origins came from a very different domain of technology development. Despite this juxtaposition, SSL stands poised to out-perform incumbent technologies such as incandescent bulbs, high-intensity-discharge lamps, and compact fluorescent bulbs in everyday applications familiar to American consumers (National Research Council of the National Academies, 2013).

Some of the excitement around SSL technology for everyday consumer applications is well-justified because SSL offers huge energy advantages in energy savings relative to incumbent technologies. SSL converts a greater amount of electricity into useful light than incumbent technologies, creating significant possibilities to reduce energy consumed for lighting. Despite the presence of high-efficiency competitors such as compact fluorescent lamps (CFLs), SSL will likely have a larger role in reducing energy consumption owing to SSL products' superior energy performance (National Research Council of the National Academies, 2013). Underscoring SSL's superior energy performance is the US Department of Energy's goal to have LED products that deliver 200 lumens-per-watt by 2025 (US Department of Energy, 2016c). With 15 percent of all retail electricity having gone to lighting in 2014 (US Energy Information Administration, 2016), reducing lighting energy consumption poses a significant opportunity for national energy savings.

⁵ LEDs cannot alone be useful toward illumination; additional components, including optical, electrical, structural, and thermal components are needed to make LED luminaires, e.g. light bulbs powered by LEDs. Throughout this work, however, the term "LEDs" and "SSL" will refer to finished light bulbs and other luminaires using semiconductor elements for illumination.

Quantifying this opportunity, LED products have been forecasted to yield a 40% savings in energy for lighting by 2030 at high levels of adoption (Navigant Consulting, 2014).

The excitement around SSL technologies' energy saving potential at high levels of adoption can be further justified by noting that SSL also proves superior in many common lighting technology performance metrics. SSL products also offer improved durability, superior aesthetic potential, superior performance in cold environments, reduced maintenance, reduced need for replacements owing to the products' long useful life, and novel form factors (National Research Council of the National Academies, 2013). Unlike CFLs and high-intensity discharge lamps, for example, SSL products are at full brightness as soon as they are powered (i.e. the light switch is flipped on). Also, application of proper control systems to LEDs can enable users to change the color of the light produced by the LED bulb. Beyond color control, LEDs with control systems can increase or decrease the apparent color-saturation of illuminated objects. Moreover, while incandescent lamps emit infrared light and therefore emit heat, LEDs do not emit infrared light and therefore have advantages in illumination for heat-sensitive applications such as illuminating art work and retail products. SSL products have long useful lives under the designed-for operating conditions, reducing the need for and cost of replacements. (National Research Council of the National Academies, 2013).

However, SSL devices appear not to have yet replaced many conventional devices, and as such much of SSL's potential appears yet untapped by consumer product markets. Despite the many advantages of SSL products, overall penetration of SSL into US illumination markets remains low. While the past 6 years have seen notable increases in the penetration of SSL into different markets and applications, thanks in part to significant reductions in price of SSL products (National Academies of Sciences Engineering and Medicine, 2017), only 6.4 percent of installed luminaires

in the US were LEDs in 2015 (US Department of Energy, 2016c). In a 2013 assessment, the National Academies of Science, Engineering, and Medicine expected that SSL lamp sales will increase as light, color quality, and cost-effectiveness are improved (National Research Council of the National Academies, 2013).⁶ Moreover, the number and size of markets that SSL technology could penetrate continue expanding, leading to greater and greater expectations for the innovative potential of SSL technology. While recent SSL product price reductions reduced profitability for LED component manufacturers, new applications for LED products have also emerged over the same period - creating new opportunities for investment and new markets for the SSL industry (National Academies of Sciences Engineering and Medicine, 2017). One of the most profound examples is the SSL systems sub-sector, which enable such applications as using the color-precision and long life of LEDs for superior horticulture and the using precise control of LED output at high frequencies for wireless communications (National Academies of Sciences Engineering and Medicine, 2017).

⁶The National Academies later assessed in 2017 that those sales increases would be contingent on meeting customer expectations for lamp reliability, establishing interoperability with control systems, and consistent delivery of high-quality light (National Academies, 2017).

CHAPTER 3. PATH-DEPENDENCIES IN INTER-FIRM R&D COLLABORATION: PHILIPS, HEWLETT-PACKARD, AND THE LUMILEDS JOINT VENTURE

3.1 Research Question

This chapter addresses the question of why, in a policy environment favorable toward inter-firm R&D collaboration, a promising SSL-focused joint venture was abandoned by one of its parent firms. Hewlett-Packard (HP) and Philips founded the joint venture firm Lumileds in the late 1990s, a time when new applications for SSL technologies seemed to be on the rise. Moreover, this was a time when US policy favored inter-firm R&D collaboration – in prior decades, US policy had generally discouraged inter-firm R&D collaboration. With the combination of HP’s expertise in the light-emitting diode (LED) SSL technology and Philips’ market reach and manufacturing expertise for all sorts of lighting products, Lumileds seemed well-positioned to capture a growing LED market.⁷ Yet in less than a decade’s time, HP’s spinoff company Agilent sold to Philips the stake in Lumileds that Agilent had inherited from HP, making Philips a near-complete owner of Lumileds (the remaining shares being owned by Lumileds employees). When faced with a policy environment favoring inter-firm R&D collaboration and a promising joint venture, why did Agilent turn away?

⁷ LED technology is what underlies most solid-state-lighting-based products available for sale at the time of this writing. The term “solid-state lighting” encompasses both LED and Organic LED (OLED) technologies. LEDs are made by combining metal elements and earth-elements into semiconductor compounds, such as Aluminum-Indium-Phosphide. Conversely, OLEDs make use of carbon-based polymers (i.e. plastics).

Part of the Lumileds joint venture's promise came in the form of generally expected high growth in markets for LED technology. In the early 1990s, HP had penetrated the automobile lighting market with high-brightness red LEDs used for taillights. This represented an important step because it was the first time in which LEDs were used for an application that specifically required high brightness. Moreover, means for creating blue LEDs were discovered in the early 1990s by Japanese researchers, which combined with existing red and green LED technologies offered the promise of creating white-light LEDs. HP's recent opening of new applications for red LEDs combined with what some observers felt was the imminent creation of a white-light LED created high optimism for LED technology. In the late 1990s and early 2000s, LED market growth was often forecast to double within the next six years. Moreover, HP was well-positioned technologically to claim much of the new market for itself.

Yet while HP's technology positioned the company well for dominating much of the growing LED markets, more than just good technology was necessary to advance LED products – and that's where Philips entered the picture. The next few sections provide a brief discussion of the complementarities between HP and Philips that undergirded the Lumileds joint venture.

3.1.1 Independent Research: HP had prior experience with LEDs, not Philips

Business reporting from years prior to the foundation of Lumileds indicates that HP was the party who brought all the SSL R&D and expertise to the joint-venture. While many articles report on SSL R&D achievements made by HP, almost no articles link Philips and SSL R&D in the years prior to Lumileds. HP's experience working with diodes as indicators for its measurement equipment appears to have formed the SSL R&D base from which HP hoped to achieve LED-based general illumination products (e.g, lightbulbs).

Long before HP had hopes for LED-based general illumination products, HP was working alongside other major US technology firms on some of the earliest LED technologies. There are at least two competing stories on the origins of HP's LED expertise. In one version, HP first acquired LED technology in 1965 through a technology license from Siemens to use LEDs for voltmeter displays in 1965 (House & Price, 2009, pp.33). In another version, HP needed microwave-emitting LEDs and in 1961 formed a joint venture with an investment group headed by local venture capitalist Jack Melchor to develop microwave LEDs (Krey, 1990), later buying the joint venture outright in 1965.⁸ Both versions agree, however, that Hewlett-Packard grew its LED business by including LEDs as a part of the instruments and devices the company sold, such as displays for calculators.

The concept of HP's SSL R&D leading the company beyond device components like calculator displays and toward lightbulb-like products appears as early as 1988, the year in which HP reported developing an Aluminum Gallium Arsenide (AlGaAs) LED for emitting red light that HP expected to introduce to automotive lighting markets (Steranka et al., 1988). In an article titled "Now a LED can take on the Light Bulb," the new AlGaAs red LED was reported to exhibit light output 125 times greater than HP's former LEDs. HP marketing engineer Chris LeBlanc attributed the red LED breakthrough to 15 years of HP R&D on infrared LEDs and low-power lasers. Because the new AlGaAs LEDs emitted bright red light, HP expected the new LEDs to compete with automotive taillights and brakelights, warning lights on radio antennae, and airport runway lights.

⁸ Far from an example of inter-firm collaboration, however, this joint-venture was very different from Lumileds in that Melchor's investment group had no technical capabilities or other expertise to complement HP's own technical expertise. Instead, Melchor's group served primarily to finance HP's technical work.

These were reportedly the first applications in which LEDs would compete with incandescent bulbs in high-brightness applications (Barnard, 1988).

Replacing incandescent bulbs in automotive lighting applications with HP's red LEDs and later orange-yellow LEDs continued to dominate the focus of HP's SSL R&D throughout the early 1990s. An article on HP's Components Group, the primary unit behind HP's LED R&D, quoted vice president and general manager of the Components Group William Craven as saying that HP's red LEDs would be in automotive taillights by 1992 (Krey, 1990). A 1994 article described HP's new orange-yellow LEDs as likely to enter automobile models by 1995 and that the market for automotive LEDs to grow to \$1 billion by 2000 (Nauman, 1994). That same year, reporting emerged on HP's release of new Gallium Phosphide (GaP) LEDs that yielded 2x the brightness of Gallium Arsenide LEDs and could provide red-orange, amber, and green light, which HP expected to make the LEDs competitive in automotive lighting (McLeod, 1994; "Technology Brief -- Hewlett-Packard Co.: New Lights Might Replace The Incandescent Lamp," 1994). Underscoring HP's uniqueness in being one of a few firms performing SSL R&D, one article also reported that only Toshiba LEDs could compete with HP LEDs and that Toshiba LEDs were still far behind HP's (McLeod, 1994).⁹ Later reports discussed improved durability for HP's automotive LEDs ("HEWLETT-PACKARD: HP supplies SnapLED automotive lighting assembly for 2000 Cadillac Deville," 1999; Wirbel, 1996). HP received the 1998 Market Engineering Product Innovation Award from market researcher firm Frost & Sullivan for the company's work on LEDs for automotive lighting ("Alternative Technologies Have OE Lighting Products Manufacturers Scrambling For Market Share," 1998).

⁹ This would appear to ignore Nichia's progress on blue-emitting LEDs but for the fact that Nichia had not produced high-brightness blue LED products comparable to HP's.

3.1.2 The forming of Lumileds: HP and Philips' knowledge complementarity

Reporting on the founding of Lumileds shows that HP and Philips exhibited strong complementarities, with HP offering its deep background of SSL R&D and recently successful LED products to the joint venture and Philips offering its product manufacturing and lighting market expertise. Underscoring Philips' extensive lighting market expertise, an early report on Philips' announcement of its intent to form an LED-focused joint-venture with HP quoted Philips' annual lighting product sales at \$7.3 billion per year ("Philips-Hewlett Joint Venture Set," 1997). Later reporting on a 1999 expansion of Lumileds beyond automotive lighting characterized the two companies as complementary world leaders: "HP is a world leader in LED technology producing a full range of colours, while Netherlands-based Philips is a world leader in developing, manufacturing and selling innovative lighting products and systems." The reporting described each firm's complementary assets as "HP's high-brightness LED (HB-LED) technologies and processes, R&D, manufacturing and sales... and Philips' market research, application knowledge and financial resources" ("HP and Philips expand joint venture advance LED adoption," 1999). In an interview with the San Jose Business Journal, Lumileds CEO Mike Holt also noted the complementarities between Philips and Agilent as being behind Lumileds foundation. "HP owned the technology to enable SSL. Philips Corp. has a high-priority need to be involved in SSL. The cultures of the two companies matched and it really was a perfect fit. What launched Lumileds was a blend of Agilent having this really awesome capability, Philips having not only the need but also the capability and knowledge of the lighting industry at large, and that became what we think is a very powerful force in the industry" (Caldwell, 2001).

3.2 Literature Review

In seeking to explain why a firm like Agilent would turn away from such a seemingly economically advantageous partnership like Lumileds, this study takes advantage of a theory developed specifically for explaining why firm behaviors fail to respond to apparent economic advantages. Namely, Nelson and Winter's theory of Evolutionary Economics puts forth an explanation for why firms fail to act in an economically rational fashion. This section provides a review of the fundamental concepts in Nelson and Winter's theory and how they will apply to this study's research question.

3.2.1 A Path-dependency theory of firm behavior: Evolutionary Economics claims Core Capabilities determine a firm's decisions

Contrary to neoclassical economic thinking, Nelson and Winter's (1982) evolutionary theory of economics regards firms' behaviors as difficult to change and firms' success or failure as a function of the fit between firms' behaviors and the firms' business environment. While neoclassical economic thinking posits firms as flexible and adaptive to signals from a hypothetical marketplace, evolutionary economic thinking posits firms as rigid and fixed in their attributes and abilities. A firm's routines and decision rules are the abilities that matter most to evolutionary economic thinking. Nelson and Winter give the name *Core Capabilities* to a firm's routines and decision-making rules. A firm establishes most of its Core Capabilities at the outset of the firm's existence – a firm's leaders decide early on ways of making oft-repeated decisions or carrying out oft-repeated tasks, and not often do the earlier decisions come into question¹⁰. Moreover, a given

¹⁰ The phrase “why mess with a winning formula” expresses human tendency to reproduce certain behavior patterns, especially in business, instead of applying scrutiny to behavior patterns already common.

business environment will reward with profits firms having certain Core Capabilities and punish with losses firms lacking certain Core Capabilities.

While firms maintain certain early-established Core Capabilities, firms can change their Core Capabilities in response to significant exogenous events – albeit not often, with great effort, not always with success, and in ways that reflect their original Core Capabilities. Tremendous shifts in marketplace demands, war, and radical technological changes serve as examples of the kind of events to which firms can respond by changing their Core Capabilities. If a firm’s leaders decide to change one of the firm’s Core Capabilities, however, evolutionary economics makes no guarantees that such a change will succeed. Many firms go through expensive attempts at internal transformations that go nowhere and leave the core of the firm unchanged. Moreover, the firm’s early-established Core Capabilities *themselves* influence (and sometimes constrain) leaders’ decisions of how to change the firm’s Core Capabilities, a constraint that reflects path-dependency. Usselman (1993) writes that “Even when a firm does change in response to the environment, those changes will strongly resemble what came before.”¹¹ Nelson and Winter write that “it is quite inappropriate to conceive of firm behavior in terms of deliberate choice from a broad menu of alternatives that some external observer considers to be ‘available’ opportunities for the organization. The menu is not broad, but narrow and idiosyncratic; it is built from the firms’ routines, and most of the ‘choosing’ is done automatically by those routines.”¹² (Nelson & Winter, 1982, pp.134-135)

¹¹ Usselman elaborates: “...Even in an industry often characterized as experiencing revolutionary change, we can detect substantial elements of continuity. The shape of the new can be seen in what came before if one looks closely at the embedded capabilities of the firms involved and pays particular attention to what Nelson and Winter refer to as the ‘programmable’ nature of their routines.” (Usselman, 1993, pp.3-4)

¹² Another good Nelson and Winter quote: ‘One cannot infer from the fact that an organization functions smoothly that it is a rational and ‘intelligent’ organism that will cope successfully with novel challenges. If anything, one should

By emphasizing how choices are carried automatically by routines instead of rational calculations, Evolutionary Economic contributes to understanding firms, industries, and regulatory systems by highlighting the real inflexibility of firms. Rather than basing policy on false predictions of smooth, rational responses to drastic changes in a business environment, policymaking benefits from a more accurate understanding of firm responses – and, in turn, so do those whom policymaking affects¹³. Nelson and Winter write that “...Efforts to understand the functioning of industries and larger systems should come to grips with the fact that highly flexible adaptation to change is not likely to characterize the behavior of individual firms. Evolutionary theory does this.” (Nelson & Winter, 1982, pp.134-135)

3.3 Hypothesis and rival hypotheses

3.3.1 Hypothesis H1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent lacked Core Capabilities suitable for inter-firm collaboration

From Nelson and Winter’s theory, we hypothesize that Core Capabilities played a role in determining the fate of Lumileds. We hypothesize that, in its early history, HP formed a Core Capability that somehow prevented the firm from forming lasting inter-firm collaborations, and that this Core Capability was inherited by HP’s spinoff firm Agilent. Further, we hypothesize that Philips in its early history formed a Core Capability that favored inter-firm collaborations, contrary to HP. HP’s Core Capabilities must have enabled the firm to prosper in its early environment, however, for this is a key stipulation of Nelson and Winter’s theory. As such, the environment

expect environmental change to make manifest the sacrifice of flexibility that is the price paid for highly effective capabilities of limited scope.’ (Nelson and Winter, 1982, pp.126)”

¹³ Moreover, scholars have applied the concepts of evolutionary thinking beyond firms behaving in a business environment. See early chapters in Mowery and Rosenberg for an application of evolutionary economic thinking to national R&D policymakers acting in a global environment. “...the “fit” between the structure of a national R&D system and its environment influences the effectiveness of that system.” (Mowery and Rosenberg, 217-218)

regarding inter-firm collaboration must have changed significantly between HP's early years and the time at which Lumileds was founded. Taken together, this hypothesis argues that Agilent ultimately abandoned Lumileds because Agilent had inherited a Core Capability from HP that somehow led Agilent away from inter-firm collaborations.

3.3.2 Rival hypothesis R1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent's expected net returns on SSL technology development fell below HP/Agilent's desired net returns from remaining in the joint-venture

Alternatively, we can take the converse of Nelson and Winter's theory – neoclassical economics – and form a rival hypothesis regarding economic signals. Neoclassical economics theorizes that firms will respond rationally to economic signals in their environment, such as rising or falling prices or regulations raising or lowering barriers to entry. As such, the rival hypothesis holds that Agilent must have abandoned the Lumileds joint venture because Agilent saw that the costs of staying in the joint venture would outweigh the benefits. Moreover, this must have changed during the course of Lumileds' existence – according to neoclassical economics, HP/Agilent would have entered the joint venture because it saw potential net gains, so for Agilent to have later abandoned the joint venture means that Agilent's perspective must have changed. In other words, the rival hypothesis is that Agilent's expected net returns on SSL technology R&D must have gone from positive to negative during the Lumileds joint venture.

3.4 Methodology

3.4.1 Testing hypothesis H1: Examining the early histories and Core Capabilities of HP and Philips, as well as changes to the business environment

To test hypothesis H1, the hypothesis derived from Nelson and Winter's theory, this analysis examines the early history of Philips and HP and any changes to the general R&D business environment specific to inter-firm collaboration. To do so, this analysis builds from prior work on the early history of Philips and HP, each firm having been covered in adequate detail by prior scholarship. For HP, this analysis relies primarily on House and Price (2009)'s exhaustive coverage of HP's history through the early 2000s. For Philips, this analysis relies primarily on work by De Vries and Boersma, scholars who have specialized in the history of Philips. This analysis also literature on the history of R&D policy as a data source on whether the R&D business environment changed between the period of either firm's early history and the time of Lumileds' existence.

3.4.2 Testing rival Hypothesis R1: Examining the life of Lumileds and HP's expected net returns from SSL technology development

To test the rival hypothesis based in neoclassical economic theory, this analysis examines reporting from the time period of Lumileds' existence for signs that expected returns on SSL R&D decreased substantially. In particular, this analysis uses the Georgia Institute of Technology's library databases subscriptions to search for articles in journals, magazines, and newspapers containing "Lumileds," "Light-emitting diode," "Hewlett-Packard," "HP," or "Philips." The analysis searched these terms in each year and collected all relevant articles from the top 40 results in each year. Frequent sources containing relevant articles included PR Wire, Business Wire, and III-Vs review, the last of which being a magazine dedicated specifically to semiconductor technologies

3.5 Findings

3.5.1 *Findings for hypothesis H1 on Core Capabilities*

3.5.1.1 The early histories and Core Capabilities of HP and Philips

Having examined the change in R&D business environment that took place between World War II and the contemporary period, we now turn to examining the experiences during this period of two firms of interest between the time of each firm's formation and the 1970s. The two firms which we will inspect, Philips and Hewlett-Packard, each acquired Core Capabilities during the companies' respective formative years. Forged by an environment of international technology competition through patents, Philips and its central research laboratory developed a Knowledge-exchange Core Capability. Conversely, the era of US R&D dominance compelled Hewlett-Packard to evolve an Innovating-from-within Core Capability. This section discusses the origins of the two company's Core Capabilities and characterizes them in some detail.

3.5.1.1.1 The Philips Company's early history

The pre-war globalized economy of the late 19th and early 20th centuries contextualized Philips' early development and motivated Philips' fast evolution of a Knowledge-exchange Core Capability. Threatened with patent lawsuits and economic competition from German lighting technology firms as well as the US's General Electric, Philips moved to work around the competition by performing its own R&D. Philips developed a Knowledge-exchange Core Capability in order to take advantage of the latest scientific developments for purposes of protecting the company from international patent lawsuits and to help the company diversify its product lines. In its early years, Philips' Knowledge-exchange capability took the form of inviting

well-known scientists to present their latest research at Philips' research laboratory. Philips' Knowledge-exchange capability later evolved into more comprehensive efforts to absorb findings from, as well as contribute findings to, the global research community. Philips' Knowledge-exchange Core Capability survived multiple changes of corporate R&D leadership and both world wars, demonstrating the true nature of Philips' Knowledge-exchange as a Core Capability.

Philips' early strategic decisions and formative changes affirm Nelson and Winter's central hypotheses by exemplifying the influence of an emerging firm's environment. Philips' formative years took place in an environment of intensive globalization – the decades from 1880 to 1920, during which global trade and industrial competition thrived. Many new multinational companies emerged, including other Dutch giants like Shell (known in the original Dutch as “Koninklijke Petroleum”) and other electrical technologies giants like Siemens and General Electric, and Philips soon became one of these new multinationals. Many of the new multinational firms exhibited vertical integration strategies, and most multinational firms in technologically growing industries founded their own research laboratories.¹⁴ Philips followed suit in both regards (De Vries & Boersma, 2005, pp.21). The similarities between Philips and its cohort of firms that emerged during the 1880-1920 globalization wave underscore Nelson and Winter's hypothesis that firms' early environment shape the firms' Core Capabilities. Moreover, the globally competitive environment of the late 1970's to present day resembles the environment of global competition that forged Philips. Philips' success in R&D joint ventures from the late 1970's to present day, discussed in further detail later, seems almost prophesied by Nelson and Winter's prediction that a firm's success is connected to the firm's environmental fit.

¹⁴ “The General Electric lab was set up in 1900, the chemical company Du Pont in 1902, AT&T between 1910 and 1912, Eastman Kodak in 1910, and Westinghouse in 1916.” (de Vries, 2005, pp.21-22)

3.5.1.1.1.1 The early Philips adapts to a global competitive business environment

In the Netherlands during 1891, Gerard Philips founded the lightbulb production company that would become the Royal Philips Electronics Company, better known as “Philips” (Boersma, 2002, pp.123). Gerard and his younger brother Anton Philips led the company during its early years. During this period, Philips’ business environment was characterized by competitive threats from the foreign firm General Electric, whose research receives credit for many of the innovations in lightbulb fabrication between 1900 and 1920. General Electric influenced European lightbulb markets by offering licenses to General-Electric-patented lightbulb fabrication technologies. European firms could attain strong competitive advantage over their European rivals through acquiring licenses to General Electric patents. Moreover, General Electric negotiated a patent agreement called the “Patentgemeinschaft” with three German firms – AEG, Siemens & Halske, and Auergesellschaft – that restricted the number of lightbulbs Philips could sell to European markets.

In response, Philips sought to work around the European sales restrictions of the Patentgemeinschaft by entering into American markets. General Electric saw Philips’ entry into American markets as a serious threat and offered Philips a unique license contract that reduced the Patentgemeinschaft’s restrictions. In 1919, Philips agreed to the license contract. During the negotiations for the license contract, however, brothers Gerhard and Anton Philips realized the risks of being dependent upon licenses to another firm’s patented technologies. Legislation passed in 1910 strengthening the Netherlands patent laws¹⁵ further augmented risks from patent licensing

¹⁵ “In the Netherlands a new patent law was passed in 1910 and the new law became effective on June 1, 1912. There had been patent legislation in the Netherlands before, but that had been abolished 43 years prior to the 1910 legislation... In the first months following June 1, 1912 [effective date of the legislation], the percentage of Dutch applications for patents was very low compared with the number of foreign applications (12% Dutch against

and patent competition (De Vries & Boersma, 2005, pp.22). Owing to the new patent risks, the brothers Philips decided to set up a research laboratory to free the company from patent licensing risks by producing new technologies owned by Philips (De Vries & Boersma, 2005, pp.19-20).¹⁶ The research laboratory, described in the next section, would come to define one of Philips' Core Capabilities that would influence its behavior later during the 1970s/1980s re-emergence of R&D global competition.

During its maturation in the early 1900s, an earlier era of global competition, Philips gained experience in global industry collaboration – and even conspiracy. Having evaded the Patentsgemeinschaft by threatening General Electric's American markets and getting General Electric to agree to a favorable licensing agreement in 1919, Philips began taking proactive steps to negotiate interfirm collaborative arrangements – some of which were anticompetitive. Philips joined the PHOEBUS cartel, known to its members as the “General Patent and Business Development Agreement”, in the 1920's to consolidate Philips position in the global market for light bulbs (De Vries & Boersma, 2005, pp.33). The Phoebus Cartel began in the 1920's and restricted the useful life of lightbulbs manufactured by its members to 1,000 hours (Dannoritzer, 2010).¹⁷

88% foreign). Foreign companies were very keen to establish sound patent positions in the Netherlands that would give them sufficient freedom to act on the Dutch market.” (de Vries and Boersma, 2005, pp.21-22)

¹⁶ As such, it is worth noting that the goal of technology R&D was to reduce legal risks, particularly risks from patent lawsuits. By contrast, improving business performance or product performance featured as strictly secondary factors motivating technology R&D – technological progress was assumed a constant of the business model, and the goal of in-house R&D was primarily to reduce legal risks to this assumed constant.

¹⁷ See also “The Parable of Byron The Bulb” in Thomas Pynchon's *Gravity's Rainbow* for further details on the PHOEBUS cartel.

3.5.1.1.1.2 Philips' Knowledge-exchange Core Capability and Philips' internal R&D division

Philips' Knowledge-exchange Core Capability, which would later influence its behavior during the 1970s/1980s re-emergence of global R&D competition, originated in the early history of the firm's internal R&D division – a division called the “NatLab”. In the winter of 1914, Gerard and Anton Philips authorized a central research organization headquartered in Eindhoven. The brothers called the research organization the “Natuurkundig Laboratorium” (abbreviated “NatLab”), which translated to English as the “Physics Research Laboratory” (Boersma, 2002, pp.124). While managers of the Philips NatLab often faced the question of how to manage researchers in the context of Philips' industrial production activities (Boersma, 2002, pp.124), the NatLab's early history – defined by its first director Gilles Holst – would influence Philips' later behaviors regarding knowledge-acquisition and knowledge-sharing activities.

Gilles Holst directed the NatLab from its inception in 1914 to the post-war leadership transition of 1946. As the NatLab's first director, Holst created organizational structures and routines that would stimulate the exchange of ideas across firm boundaries. Holst created an academic culture different from that of the rest of the Philips firm, keeping the NatLab organization as informal as possible and allowing individual scientists to prosper. Holst directed NatLab researchers to exchange knowledge with others inside and outside the firm through participating in committees and regular gatherings (Boersma, 2002, pp.127). Holst's emphasis on knowledge exchange inside and outside the firm enabled the NatLab to provide Philips with a source of cutting-edge knowledge on early-20th-century electrical technologies. Rather than “leaking” knowledge outside of Philips, however, the activities of Holst's NatLab enabled Philips to initiate a patent strategy that led to enormous profits from NatLab research (Boersma, 2002, pp.127).

Holst encouraged the Knowledge-exchange Core Capability of the NatLab through many concrete actions. Holst organized NatLab-hosted colloquia and symposiums at which world-famous physicists, such as Einstein, Meitner, Born, Pauli, Geiger, and even General Electric's Langmuir, shared their research and perspectives with NatLab scientists. The colloquia and symposiums continued from 1924 through 1942, when the colloquia were paused to protect scientific secrets during World War II. Furthermore, Holst directed NatLab scientists to share their work with the world through publication in scientific journals, seeking to bolster the reputation of Philips and encourage top scientists to work at the NatLab. While Philips published only one article in 1914, the earliest year in Philips' publication record and prior to the NatLab's foundation, Holst managed to get NatLab scientists to increase publication until achieving a rate of 236 papers per year in 1937. NatLab publication declined during World War II in order to protect technological secrets but recovered after the war ended (De Vries & Boersma, 2005, pp.60). Moreover, Holst encouraged knowledge exchange beyond the firm by attracting scientists from universities and encouraging universities to recruit faculty from among the NatLab's researchers. Several NatLab researchers left the NatLab to become professors at leading universities such as Utrecht and Leyden. Holst himself helped established the Netherland's first polytechnic university at Delft, and two NatLab researchers became some of the first faculty there (De Vries & Boersma, 2005, pp.55-58). Finally, Holst also created an independent journal through which the NatLab could communicate its findings to industry. In 1936, the NatLab published the first volume of the Philips Technisch Tijdschrift (Philips Technical Review). Holst's own introduction to the first volume states that the intent of the journal is to encourage exchanges with the broader engineering community regarding Philips products. The journal published in Dutch, English, German, and French, and put out 12 issues per year (De Vries & Boersma, 2005, pp.60).

3.5.1.1.1.3 The NatLab's early patent production system as a response to global R&D competition

Philips' early experience of its business environment had taught the company's early leadership about the importance of maintaining a legal advantage through patents. General Electric's Patentsgemeinschaft with lightbulb manufacturing companies in other European nations compelled Philips to recognize the importance of patents and devote considerable resources and strategy toward a business model that accounted for and mitigated patent-related legal risks. As such, Philip's early leadership created the NatLab with the goal in mind of using R&D to produce patents and attain the upper hand over competitors through a strong patent portfolio that translated to a strong legal position. Would Holst's Knowledge-sharing strategy for the early NatLab thwart the company's overall patent-portfolio strategy?

No. Rather than thwarting the lessons learned during Philips' early history regarding the importance of a legal advantage through patent portfolios, Holst's commitment to developing a Knowledge-exchange Core Capability dovetailed with the goal of using the NatLab for patent advantage. Carrying forward the legacy of the Philips' brothers' decision to found the NatLab to attain advantage in patents, Holst implemented a rigorous system for developing NatLab-research-based patents. Holst expected NatLab scientists to develop ideas for patents based upon the scientists' work, and he explicated this expectation. Holst created a small form, called a White Card, that NatLab scientists were required to complete on all patent ideas. Upon receiving a White Card, Holst himself would decide whether or not the potential patent possessed merit sufficient to be worth forwarding to Philips' internal patent department. If Holst decided not to forward the patent idea, he would instead allow the researcher to publish the work in an academic journal. If Holst forwarded the patent idea to Philips' patents office, Holst would direct the researcher to

refrain from publishing until the Netherlands' national patents office registered the application. Between the NatLab's inception in 1919 and 1940, each NatLab scientist submitted between 1 and 4 White Cards per year (De Vries & Boersma, 2005, pp.22).

3.5.1.1.1.4 Philips continues knowledge-exchange in the age of US R&D dominance

Far from being idiosyncrasies that lasted only under Holst's direction and evaporated thereafter, the Knowledge-exchange Core Capability persisted after Holst's departure and the arrival of new NatLab director Hendrik Casimir, who directed the NatLab from 1946 to 1972. Casimir had earned worldwide renown as a physicist who had performed fundamental scientific research with Bohr, Pauli, and Ehrenfest in the 1920s. Casimir assumed directorship in 1946, the dawn of a boom-time for fundamental scientific research. Vannevar Bush's 1945 report "Science – The Endless Frontier" (V. Bush, 1945) captured new, widespread favorable attitudes and expectations and inspired government leaders around the world to invest in fundamental scientific research (Dennis, 1997). As such, Casimir's own views of the role of fundamental scientific research fit well within the contemporary zeitgeist (Boersma, 2002, p.128).

While pursuing fundamental scientific research, Casimir also enacted knowledge-exchange through connecting the NatLab to other scientific research institutions. Casimir encouraged NatLab researchers to keep in touch with scientists all over the world, claiming that research is an international activity and duplication is useless. Casimir himself took interest in new natural science findings and theories, and always investigated whether a new scientific finding or theory could be absorbed into the NatLab's research program. Casimir also measured the success of the NatLab in ways similar to how one might measure the success of a university or other scientific institution – in terms of the number of scientific articles published, technical reports produced, and

patents acquired (Boersma, 2002, p.128). Casimir's encouragement of knowledge exchange inside and outside the firm enabled the NatLab (and Philips) to influence the latest technological developments worldwide. Casimir made reviews of the latest scientific research a regular priority for the NatLab (Boersma, 2002, p.129). Casimir also expanded the NatLab's absorptive capacity by scanning the latest scientific developments. According to De Vries and Boersma, at conferences on Philips' corporate research agenda (the CRCs), "...Casimir always asked the question of whether a certain new theory or field could be absorbed into the NatLab's research programme. Thus, a careful scanning of the latest scientific developments under his leadership became a continuous item at the top of the CRC's agendas." (De Vries & Boersma, 2005, pp.132)

Casimir also maintained Philips' Knowledge-exchange Core Capability through continuing the connections to prominent Dutch universities – in other words, NatLab continued exchanging knowledge with universities through exchanging personnel. Between 1946 and 1972, the wide majority of scientists coming to the NatLab came from Technische Hogeschool Delft (Delft Polytechnic). The NatLab also drew scientists from Eindhoven Polytechnic and the Universities of Amsterdam, Utrecht, Leyden, and Groningen. Moreover, Philips maintained contact with universities through 'buitengewone' (extraordinary) or 'bijzondere' (special) professors who worked both for the Philips NatLab and one of the universities. The professors helped the NatLab maintain knowledge on both the most recent scientific developments and potential scientist-recruits to the NatLab (De Vries & Boersma, 2005, pp.134)

De Vries summarizes the NatLab culture as possessing great strength in its knowledge-exchange Core Capability. De Vries states that in the NatLab, "...there was a constant search for new scientific fields or important external progress in existing fields that might be relevant for the NatLab. to take up." (De Vries & Boersma, 2005, pp.136)

3.5.1.1.2 Hewlett-Packard's early history

Contrary to Philips' origins in a global competitive environment, Hewlett-Packard's early evolution in the age of US R&D dominance compelled the company to develop a sensitivity and responsiveness to the US technology markets. While the global R&D business environment may not have been competitive, the US environment was. Hewlett-Packard competed during its early years on equal footing against a handful of other US firms in what began as niche technology markets. HP's leadership oriented the company towards competition in niche markets, decentralizing decision-making as much as possible to enable the product-focused company to compete with maximum flexibility and agility. Conversely, the company rarely engaged in exchanges of knowledge with other companies or universities. Instead, the early Hewlett-Packard looked to its own veteran engineers and new hires for new ideas on how to stay competitive. HP developed a culture of pride in its own people and a focus on getting new ideas from its own employees. That is, HP never developed a Core Capability like Philips' Knowledge-exchange with sources outside the firm. Instead, Hewlett-Packard's Core Capability of Innovating-from-within helped the company survive, thrive, and expand during the age of US R&D dominance. The unipolar environment of US dominance in R&D from the 1940's through the 1960's favored HP's use of one's own personnel for new ideas, but changes to the environment in the 1970s and 1980s challenged HP's ability to succeed.

3.5.1.1.2.1 Hewlett-Packard's origins: The do-it-yourself birth of Silicon Valley

Bill Hewlett and David Packard, both engineering graduates of Stanford University, founded HP in 1939 at the dawn of what was to become the golden age of US corporate R&D. Hewlett's creation of a user-friendly variable-resistance circuit motivated the pair to create the

company, which soon afterward earned a sales contract from Disney Studios when Disney found use for Hewlett's creation in the upcoming recording of the Fantasia soundtrack. Disney's need for advanced measurement technologies to mix tracks with precision from the symphony recordings for Fantasia foreshadowed the precision measurement technologies that would become the early HP's main line of business. Hewlett and Packard established HP's first operating location in David Packard's personal garage in Palo Alto, CA – later recognized by an Institute for Electrical and Electronic Engineering (IEEE) memorial as “the birthplace of silicon valley.”

In the early years, HP acquired good R&D knowledge by acquiring top researchers from universities. HP authorized its product development engineers to make hiring decisions, allowing the actual engineers to perform interviews and recruit prospective employees. HP also focused its recruitment efforts on top engineering schools in the nation such as Stanford but also including other top universities like Princeton. HP also reached into universities by offering fellowships and internships. Upon a student's acceptance of an HP fellowship, Packard or Hewlett would ask the student to research a particular field and develop a related novel technology proposal. Often the student's proposal would make its way into HP's R&D efforts and into a product. Such was the case with Al Bagley, a young Stanford engineer who earned an HP fellowship, researched atomic measurement, and proposed a measuring device that became the HP-524A Electronic Counter for measuring nuclear phenomena (House & Price, 2009, pp.21).

3.5.1.1.2.2 Hewlett-Packard develops a Core Capability of Innovating from Within

Of great importance, HP's engineers derived much of their new ideas from customer outreach and from conversations with HP's leadership. Rather than studying new scientific developments related to their products or attending conferences to exchange ideas with engineers at other firms,

HP engineers visited customers and discussed new ideas with HP leadership for inspiration. As examples, HP engineer Bruce Wholey often visited Hughes Aircraft facilities for purposes of demonstrating and receiving feedback on HP's waveguide equipment. Don Hammond, HP's lead researcher in crystallography, spent many hours discussing new ideas and inventions with Hewlett and Packard in person. Hammond described the discussion as involving intensive detail and thought-experimentation: "Bill and Dave would review it and say 'Why didn't you do that? Or that? Well, I think you'd better take it back and work on it a bit longer.'" (House & Price, 2009, pp.23) More academic personnel, such as Dr. Barney Oliver who first led the HP labs after its inception in the 1960s, drew some ideas from private reviews of scientific literature in fields such as lasers (House & Price, 2009, pp.24). But Oliver's approach remained the exception at HP, where engineers were looking to their markets and to their leadership for ideas. As lead engineer Al Bagley described, a new engineer at HP got ideas from self-initiated market research and through a review process that included Hewlett and Packard themselves (House & Price, 2009, pp.29-30).

To further enhance its niche-market sensitivity, the early HP decentralized its decision-making as much as possible – including decisions about R&D. Engineers were expected to come up with new ideas, not only for existing products, but also new products, production processes, and even the design and functioning of the HP organization itself. Although Hewlett and Packard were crucial in shaping the R&D direction of HP, Hewlett and Packard did not exercise unilateral authority over HP's R&D direction – indeed, the R&D direction of HP was often shaped by HP's own engineers. As an example, House and Price 2009 argue that HP made six major shifts in its product portfolio over the course of HP's existence with David Packard resisting all six major changes and Bill Hewlett resisting all but one. House and Price credit the success of the product

transformations against Packard and Hewlett's objections to HP's corporate culture of encouraging "maverick" engineers to develop and pursue their own ideas (House & Price, 2009, pp.33).

Beyond HP routine of looking inward for new ideas, HP also often looked inward for new leadership. Hewlett and Packard both believed that HP's management and senior leadership should come from people who had been with the company for many years and who were embedded in and would promulgate HP's culture (and Core Capabilities). Hewlett and Packard both disfavored hiring executives from the outside, and the company as a whole disdained outside management fads and popular business practices (House & Price, 2009, pp.30). Monthly executive meetings and annual summits would be focused on internal business practices and performance – there would never be any visiting speakers presenting on new, interesting topics. As former HP Executive Vice President Bill Terry put it, "it was technology and business – it was not visiting speakers talking about interesting things." (House & Price, 2009, pp.30) The survival of HP's preference for pulling leadership from its own veteran employees would become apparent decades later when current and former employees rankled at the HP board's decision to hire first Caryl Chessman and then Mark Hurd, "guru" executives who were total outsiders to HP (House & Price, 2009, pp.30).

3.5.1.2 The change in the US R&D business environment that occurred in the 1980s

Since Nelson and Winter's theory requires a changing business environment to demonstrate the differences in fitness between firms and their Core Capabilities, this section characterizes the changing R&D business environment of the late 20th century. While the US dominated global R&D – both in funding and performance – from the late 1940s to the early 1970s, a rise in global competition in the late 1970s and throughout the 1980s challenged the position of US firms in

R&D-intensive industries. Non-US firms' technological competencies began to match or outpace those of US firms, leading to increased competitive pressure on US firms. US firms that only rarely collaborated with one another or with non-US firms during the age of US dominance responded to the 1970s rise in global competition with increased inter-firm collaboration. After a wave of US policy responses throughout the 1980s, the new normal of the R&D business environment emerged – featuring a diversification of research funding structures and performers.

3.5.1.2.1 The 1940s-1960s anti-collaborative R&D policy environment

The environment after World War II and prior to 1980 featured US funding and US firms dominating R&D performance around the world. US firms performed much of their own R&D and captured most of the benefits of university R&D. Corporations also performed most of the R&D in the US by a wide margin, in contrast to universities¹⁸. Moreover, most of the world's R&D was performed by US firms, and non-US firms sought to follow the US firms' technology leadership. Most R&D during the post-World-War-II environment drew support from US federal funding, and the US provided more support to R&D than any other nation. (Mowery & Rosenberg, 1989, pp.205). Most US exports after World War II consisted of R&D-intensive goods (Gruber, Mehta, & Vernon, 1967; Mowery & Rosenberg, 1989).

The US federal government's role in funding R&D meant that US policy had significant impact on the world's R&D performance, and this was particularly important for inter-firm R&D collaboration. Importantly, US policy deterred inter-firm collaboration on R&D through a variety of mechanisms. Two of the most important were threats of anti-trust action and withholding of

¹⁸ Universities would later grow to take a large share of R&D performance, and US corporations' share of total US R&D performed would later decline.

federal funding for R&D performance. Firms that collaborated on R&D activities could be prosecuted by the federal government under anti-trust law for conspiring to manipulate markets. Moreover, many US R&D funding programs made non-collaboration with other firms a condition of R&D funding. As such, firms who wished to receive US funding for R&D – the primary source of funding for the world’s R&D – were deterred from collaborating with other firms by the policy environment existing from the 1940s through the 1970s.

3.5.1.2.2 The 1970s move toward inter-firm collaboration and international competition

Toward the end of the 1970s, however, it became clear that the era of US policy’s influence over R&D performance had come to an end – both through the rise of non-US R&D performers and through a rise in inter-firm collaboration, both domestically and internationally. A trend toward technological equality between the US, Western Europe, and Japan emerged during the late 1970s and continued into the 1980s, with scholars noting the prior period of US dominance as exceptional and unsustainable (Langlois, Pugel, Harklisch, Nelson, & Egelhoff, 1988; Mowery & Rosenberg, 1989, pp.237). Increasing rates of international technology transfer in the 1980s brought special challenges to the US economy, whose exports were based more on R&D-intensive goods than the exports of other industrialized nations (Organization for Economic Cooperation and Development, 1986). Improvements in the technological capabilities of non-US firms and non-US economies strengthened their ability to learn from and transfer US-firm and US-economy R&D and technologies to the non-US firm’s own markets – increasing the “global mobility” of technology (OECD, 1979; Mansfield and Romeo, 1980; Mansfield, 1985; Abramovitz, 1986). In contrast to the low international competition during the period of exceptional US dominance in world trade, 70 percent of US manufacturing output faced international competition during the 1980s (Aho,

1988). The drastic increase in international economic competition led many to predict the demise of US regional technology hubs, such as silicon valley (Arora, Branstetter, & Drev, 2013).

In addition to international competition, inter-firm collaboration began to increase both domestically and internationally. US firms sought to leverage the new expertise of non-US firms in collaborative R&D partnerships that increased drastically in number throughout the 1970s and 1980s. While joint ventures weren't new to US firms, nor even joint international ventures, the joint ventures of the 1980s differed in substantial ways from joint ventures typical of the 1950s and 1960s (Mowery and Rosenberg 242). Mining and extraction industries, such as the coal, oil, and natural gas industries, have long made use of traditional joint ventures (Stuckey 1983). But during the 1970s and 1980s, joint ventures began to appear in many industries that had not before seen much interfirm collaboration (Harrigan 1984; Harrigan 1985; Hladik 1985). While international collaboration was rare during 1945-1970 in the commercial aircraft industry, for example, the industry featured some of the highest rates of international inter-firm collaboration by the late 1980s (Mowery, 1987). Figure 2 shows the trend of a rapidly rising number of R&D-focused inter-firm collaborations over this period.

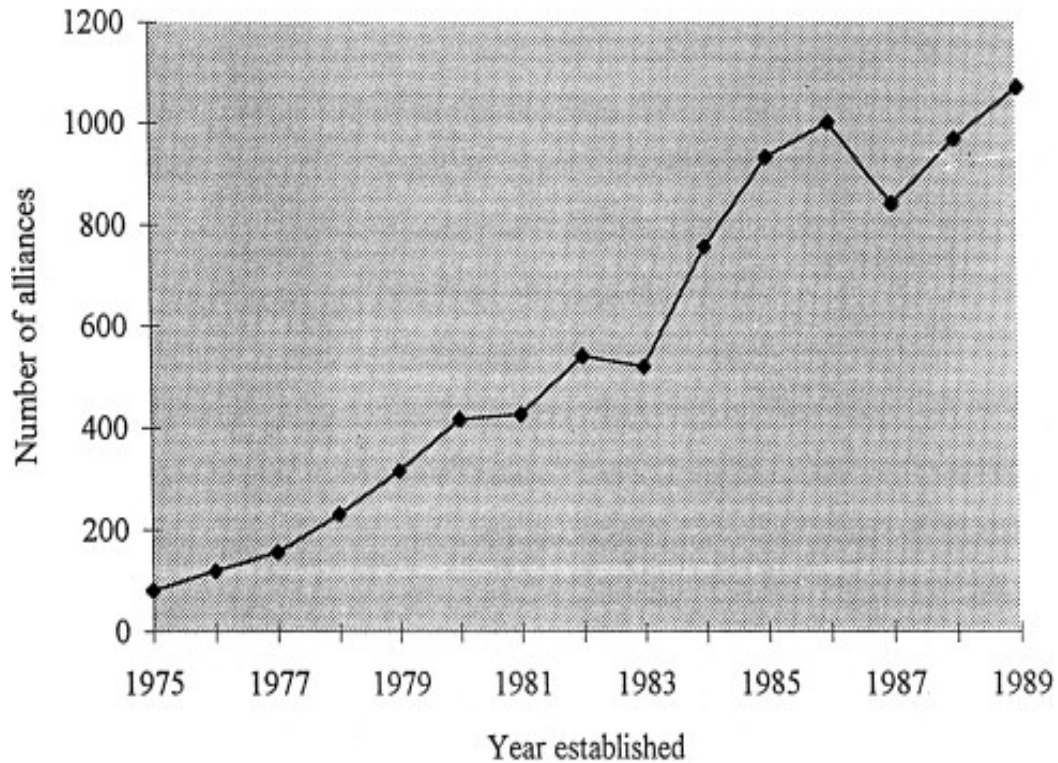


Figure 2: Contrary to the anti-collaborative period of the 1940s, 1950s, and 1960s, the number of R&D-focused inter-firm collaborations (here the term “alliances” is used) increased dramatically throughout the 1970s and 1980s. Source: (David C. Mowery & Rosenberg, 1989)

3.5.1.2.3 US policies establish new R&D structures in the 1980s

The 1980s saw US federal legislators reacting to the rise in US firm collaborations with US and non-US firms through a variety of new laws. The US began by encouraging its constituent states to hold and license patents from federally funded research through the Stevenson-Wydler Technology Innovation Act of 1980. Federal legislators hoped the Act would reduce technology transfer to non-US firms and increase the returns to US-funded research received by US firms (Hounshell, 1996, pp.54). In 1981, US legislators passed the Bayh-Dole Act to allow universities to hold patents from federally funded research and further slow technology transfer to non-US firms. Despite the seeming retrenchment effort by the two acts, however, the US soon began a

string of policies intended to capitalize on and accelerate participation of US firms in the global market for technology. For example, the 1983 Modified Final Judgement in the case of US v AT&T ended the AT&T monopoly on telecommunications but also enabled AT&T to begin competing in foreign telecommunications markets. Perhaps the most symbolic US policy, the 1984 National Cooperative Research Act, forbade anti-trust action against firms engaged in collaborations focusing on pre-commercial R&D (David C. Mowery & Rosenberg, 1989, pp.253). Later acts focused on government-performed R&D; the 1986 Federal Technology Transfer Act and the 1989 National Competitiveness Technology Transfer Act enabled US national laboratories, including contractor-operated laboratories, to globally market the laboratories' technologies (Hounshell, 1996, pp.54). The US also encouraged university-industry partnerships via funding support, for example through SEMATECH and the National Center for Manufacturing Sciences. However, Mowery and Rosenberg (1989) found government funding absent from collaborations between US firms and between US and non-US firms. The lack of government funding for inter-firm collaboration in the US contrasted the experience in Western Europe and Japan, where public funding played a strong role in supporting inter-firms collaborations such as the Airbus Industrie consortium (Mowery & Rosenberg, 1989).

3.5.1.2.4 The 1990s and onward favor inter-firm collaboration

The rise of global trade competition and global technological competence shocked the US R&D system into a transformation away from a federally funded, corporation-dominated model and toward a matrix model of collaborations between firms, universities, and governments. The US government and its corporations established many diverse new R&D structures such as:

- firms pooling money together in R&D collaborations, sometimes with funds from government, sometimes with involvement of foreign firms

- subcontracting to a different firm or a separate R&D unit
- keeping all R&D in-house (as with Intel)
- partnering with universities or funding university-based consortia, and
- acquiring intellectual property from universities or other firms

Increasing global diversification of the opportunities and mechanisms for performing R&D marked the 1980s and 1990s (Hounshell, 1996, pp.57). Hounshell writes that “...the 1980s and early 1990s brought about a crazy quilt of avenues, approaches, and opportunities for corporate R&D managers. The array of ways to spend money on R&D became staggering, especially in light of the increasing globalization of business, which had begun before the end of the cold war.” (Hounshell, 1996, pp.54). Contemporary examples of Hounshell’s “quilt” that may be familiar to the reader include:

- The US National Nanoscience Initiative
- The US National Science Foundation’s EPSCOR program
- The US Department of Energy’s Energy Frontier Research Centers (EFRCs)
- The US National Science Foundation’s Engineering Research Centers (ERCs)
- Cooperative Research and Development Agreements (CRADAs)
- Memoranda of Understanding (MOUs) between partners to an R&D effort
- The US Department of Energy’s loan guarantee programs

3.5.1.3 Differences between HP and Philips in terms of inter-firm collaboration

While both Philips and Hewlett-Packard responded to rising international competitiveness by increasing collaborations with other firms during the 1980s, the two companies’ Core Capabilities

drove them to differ in both degree and kind of inter-firm collaboration. Philips' Knowledge-exchange capability enabled Philips to begin collaborating early in the onset of inter-firm collaborations that would mark a trend in the 1980s. Conversely, Hewlett-Packard's attempted shift in Core Capabilities from failed to boost the company's collaboration. Hewlett-Packard's Innovating from Within in particular drove the company away from collaboration, and only after the mid-1980s conversion to Integration and to the computer systems industry did the company increase collaboration. The influences of the two companies' respective Core Capabilities on collaborative behavior reveal themselves in data from a key academic study of 1980s inter-firm collaboration.

A definitive empirical study of Strategic Technology Alliances throughout the 1980s provides information on the R&D collaboration activities of major individual firms, including both Philips and Hewlett-Packard. Researchers John Hagedoorn and Jos Schakenraad (1992) performed an extensive study of inter-firm collaborations throughout the 1980s related to strategic technologies. The study used the Cooperative Agreements and Technology Indicators (CATI) database¹⁹, which contains records of about 10,000 agreements between about 3,500 parent firms. Among the CATI's thousands of records, Hagedoorn and Schakenraad identified 4,000 of the agreements as Strategic Technology Alliances, a term the researchers use to characterize agreements related to R&D and technologies. Hagedoorn and Schakenraad further characterize strategic Technology Alliances as agreements focused on the transfer of technology or the creation of a new technology

¹⁹Researchers formed the CATI by collecting records from newspaper and journal articles, business/industry press, and books on inter-firm collaborations. The CATI's curators used company annual financial reports, *Financial Times Industrial Companies Yearbooks*, and Dun & Bradstreet's *Who Owns Whom* to figure out identities of dissolved joint-ventures and similar collaborations.

through R&D. The researchers write further that Strategic Technology Alliances include joint ventures centered on technology, research corporations, joint R&D pacts, and minority holdings attached to research contracts. Hagedoorn and Schakenraad acknowledge the purposive omission of any agreements related to marketing, production, or sales. Moreover, the researchers also exclude government-funded cost-sharing programs, such as the US SEMATECH program or the EU's ESPRIT and EUREKA programs, to better-understand patterns of privately supported collaborations. Hagedoorn and Schakenraad also make one further restriction on the data studied – that of limiting their analysis to various subfields of the Information Technology industry. The researchers focus on Information Technology because other work finds 42% of Strategic Technology Alliances in the CATI database come from the Information Technology industry. The study therefore covers 1,700 of the agreement records in the CATI database from the Information Technology subfields of computers, industrial automation, micro-electronics, software, and telecommunications (Hagedoorn & Schakenraad, 1992). Hagedoorn and Schakenraad's analysis shows Philips to have outpaced Hewlett-Packard in inter-firm collaboration.

Hagedoorn and Schakenraad's analysis shows that Philips is among the leading firms for inter-firm collaboration in both 1980-1984 and in 1985-1989, showing that Philips Knowledge-exchange capability enabled the company to collaborate early and often. Conversely, Hagedoorn and Schakenraad's results show Hewlett-Packard only ranking in the middle for Software from 1980-1984 and climbing to the top only for Software during 1985-1989.

Table 6, taken from Hagerdoorn and Schakenraad's analysis, shows the collaboration numbers for Philips and Hewlett Packard by subfield. It is revealing that Hewlett-Packard's collaboration in software drives the company's upswing in collaboration overall. While Hewlett-Packard had been present in the computer industry – and even in all of the subfields listed here – only in the 1980s did the company shift toward the Integration Core Capability and accept its new path as a software and systems integration leader. Conversely, Philips shows as a strong collaborator in multiple subfields of IT – Industrial Automation, Computers, and Micro-electronics.

Table 6: Inter-firm collaboration ranking results from Hagedoorn & Schakenraad (1992).

| Information Technologies | | | | Software | | | |
|--------------------------|----|---------------|-----|------------------|----|---------------|----|
| 1980-84 | | 1985-89 | | 1980-84 | | 1985-89 | |
| 1. Motorola | 53 | Siemens | 134 | 1. CDC | 18 | HP | 47 |
| 2. Siemens | 51 | Philips | 127 | 2. NCR | 16 | DEC | 45 |
| 3. IBM | 48 | Olivetti | 110 | 3. Honeywell | 14 | Siemens | 36 |
| 4. Sperry | 47 | IBM | 108 | 4. Motorola | 14 | Bull | 34 |
| 5. Fujitsu | 46 | HP | 96 | 5. HP | 13 | AT&T | 33 |
| 6. Olivetti | 42 | DEC | 95 | 6. Sperry | 13 | Philips | 32 |
| 7. CDC | 41 | AT&T | 90 | 7. Allied | 12 | SUN-microsys. | 31 |
| 8. Intel | 41 | Thomson | 83 | 8. AMD | 12 | NCR | 29 |
| 9. Philips | 40 | Fujitsu | 78 | 9. DEC | 12 | Volmac | 29 |
| 10. NEC | 39 | Motorola | 68 | 10. Harris | 12 | Olivetti | 28 |
| Computers | | | | Microelectronics | | | |
| 1980-84 | | 1985-89 | | 1980-84 | | 1985-89 | |
| 1. Sperry | 27 | Olivetti | 22 | 1. INTEL | 34 | Thomson | 51 |
| 2. IBM | 19 | CDC | 19 | 2. Motorola | 23 | INTEL | 46 |
| 3. CDC | 18 | Unisys | 17 | 3. Philips | 20 | AMD | 42 |
| 4. Olivetti | 17 | Bull | 14 | 4. Thomson | 19 | Motorola | 40 |
| 5. Fujitsu | 15 | Philips | 13 | 5. Toshiba | 18 | Philips | 39 |
| 6. NEC | 12 | Fujitsu | 12 | 6. Siemens | 17 | Texas Inst. | 37 |
| 7. Burroughs | 11 | NEC | 12 | 7. Fujitsu | 16 | Siemens | 36 |
| 8. Toshiba | 10 | SUN-Microsys. | 11 | 8. NEC | 16 | IBM | 30 |
| 9. DuPont | 10 | DEC | 10 | 9. EXXON | 15 | Toshiba | 27 |
| 10. 3M | 10 | Hitachi | 10 | 10. AMD | 14 | AT&T | 26 |
| Telecommunications | | | | | | | |
| 1980-84 | | 1985-89 | | | | | |
| 1. Siemens | 17 | Siemens | 45 | | | | |
| 2. AT&T | 15 | CGE | 32 | | | | |
| 3. ITT | 14 | Sumitomo | 29 | | | | |
| 4. Fujitsu | 10 | Mitsubishi | 28 | | | | |
| 5. IBM | 10 | Fujitsu | 27 | | | | |
| 6. Plessey | 10 | AT&T | 26 | | | | |
| 7. Hitachi | 9 | Philips | 26 | | | | |
| 8. ANT | 8 | IBM | 24 | | | | |
| 9. NEC | 8 | NEC | 23 | | | | |
| 10. Olivetti | 8 | Ericsson | 20 | | | | |

Hagedoorn and Schakenraad (1992) also map the network of inter-firm collaborations during the study period, shown in Figure 3 and Figure 4. The maps support the numbers in Table 6, showing

Hewlett-Packard (HP) isolated during 1980-1984 but integrated during 1985-1989. Conversely, Figure 3 and Figure 4 show Philips integrated in both periods.

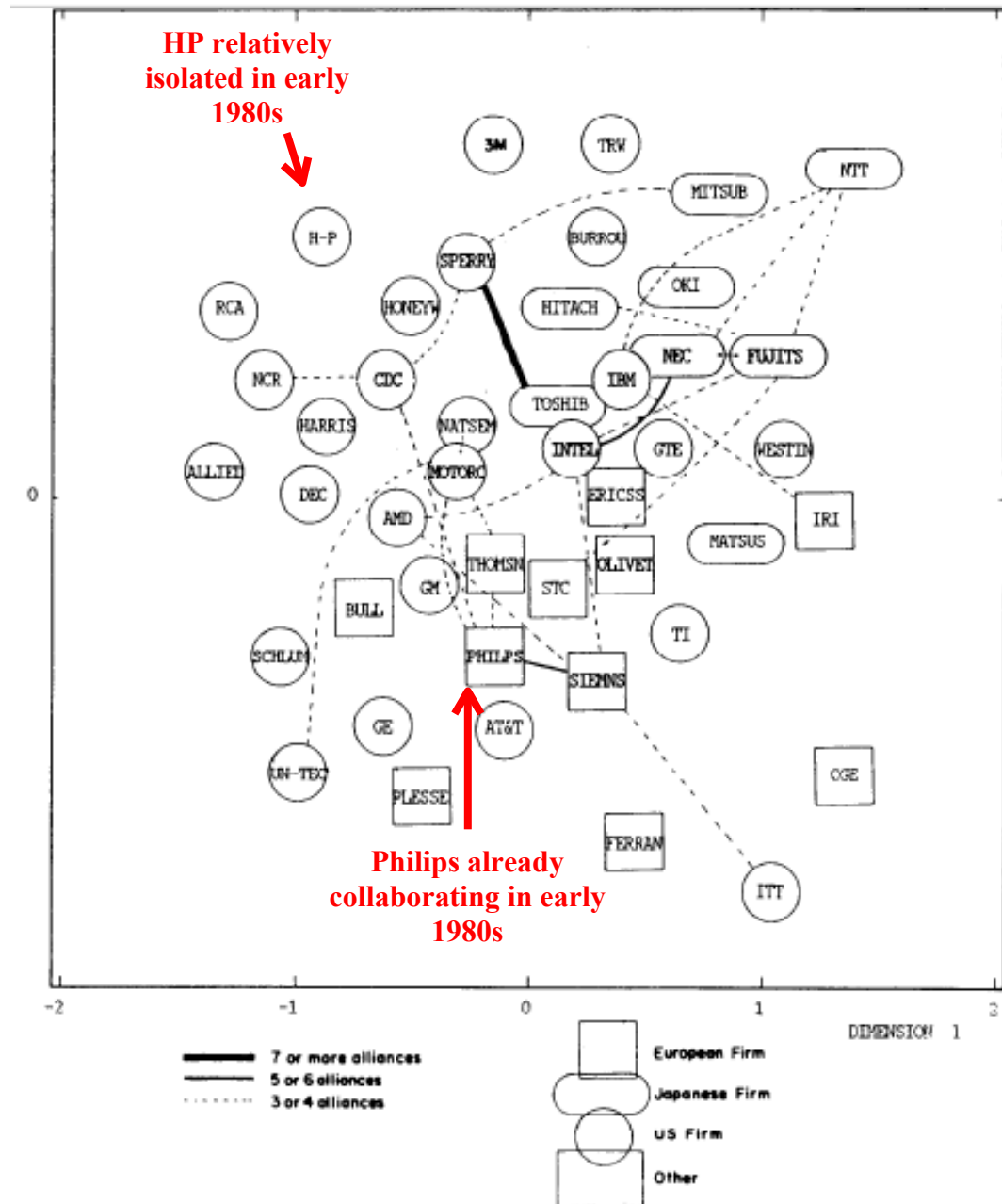


Figure 3: Structure of collaborative partnerships between firms between 1980 and 1984.
Source: Original figure from Hagedoorn & Schakenraad (1992)

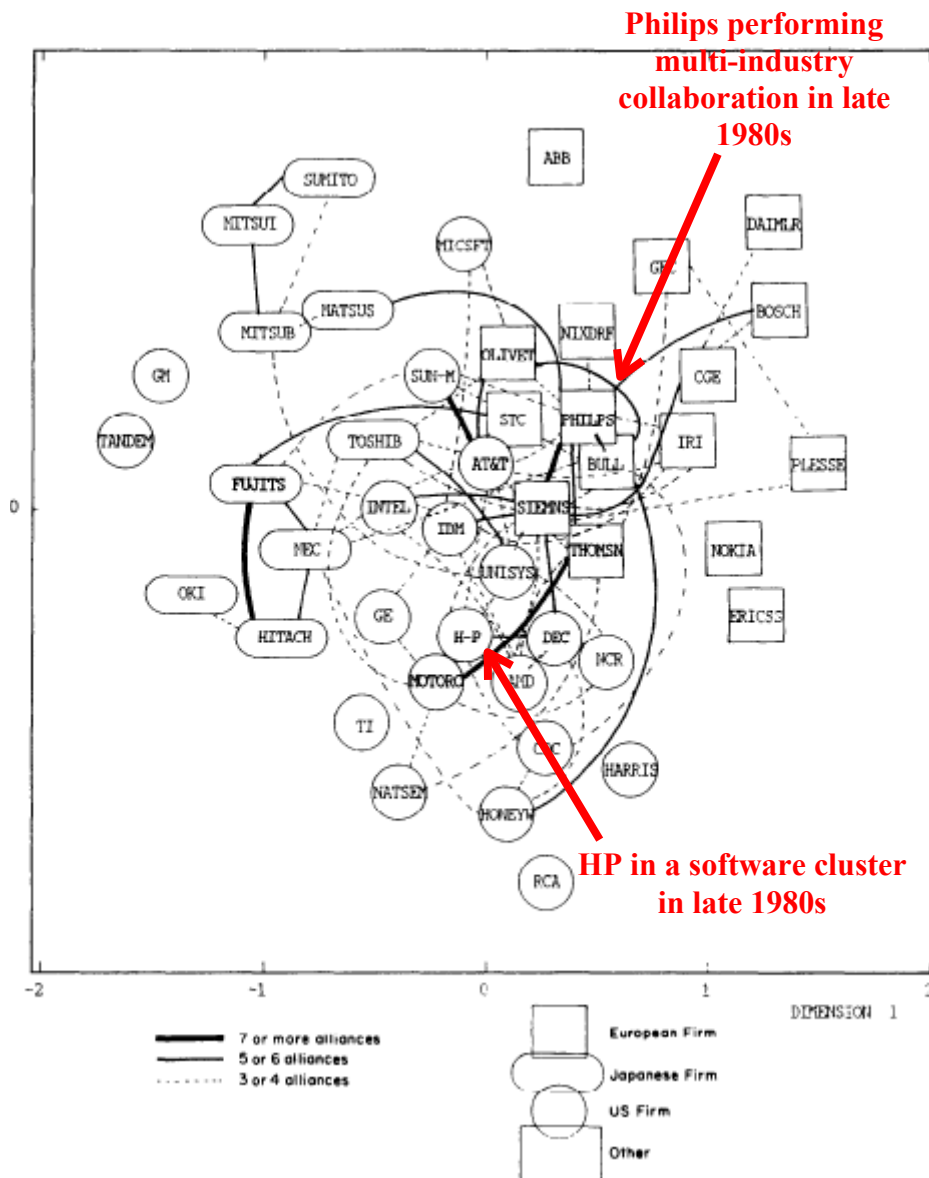


Figure 4: Structure of collaborative partnerships between firms between 1985 and 1989.
Source: Original figure from Hagedoorn & Schakenraad (1992)

In their own analysis of the data, Hagedoorn and Schakenraad find evidence that collaboration is indeed tied to firm-specific characteristics, such as Core Capabilities: “In sub-fields of information

technologies, where the number of potentially relevant firms can be expected to be smaller, we found significant rank correlations [i.e. correlations between 1980-1984 rankings and 1985-1989 rankings, i.e. persistence of certain firms in each ranking], with the exception of software [in which HP rises to the top from having not ranked at all]. This means that in computers, industrial automation, microelectronics, and telecommunications, some firms indeed do leave and others enter the group of most collaborative companies, but the rankings of the remaining companies did not change significantly.” (Hagedoorn & Schakenraad, 1992, pp.183) “In general the conclusion has to be that there is no clear correlations between both rankings [of sales leadership and of collaboration in IT], it is obvious that the leading companies are well-represented among the most collaborating companies, without quantitatively dominating the general network of strategic technology alliances.” (Hagedoorn & Schakenraad, 1992, pp.185)

Why had Hewlett-Packard collaborated in software, and in no other sectors? Why did such a prominent technology firm as Hewlett-Packard not engage in more collaborative joint-ventures, when comparable firms around the world were doing just that? Conversely, why had Philips collaborated in so many industries and with such great effort? Hewlett-Packard had attempted a change in its Core Capabilities in efforts to transform into a firm compatible with the computer systems industry. Hewlett-Packard’s efforts were only successful in part – the firm’s original Core Capabilities remained within it after the transformation, and continued to chafe at the firm’s new directions. Hewlett-Packard’s lack of collaboration came from the firm’s early history that biased it against collaboration and instead encouraged the firm to look for new ideas from within. Hewlett-Packard’s collaboration only in software represented the firm’s recent attempts to change its culture, to change its Core Capabilities, and its recent acquisition of a leadership team from IBM. Unlike Hewlett-Packard, IBM ranks near the top on more than one of Hagedoorn and

Schakkenrad's tables. Conversely, Philips' strong collaboration throughout the 1980s in multiple industries represents the early history of Philips' NatLab which guided the firm toward collaboration and knowledge-exchange with R&D workers at other firms.

3.5.2 Findings for rival hypothesis R1 on HP's expected net returns from SSL technology development

Primary sources on Lumileds reveal four indicators of HP's expected returns from SSL technology: (1) Lumileds' successful new product releases and product performance milestones, (2) Lumileds' new sales contracts and revenue, and (3) Lumileds' litigation over patent disputes and the associated risk, and (4) forecasts of the LED market's future growth. The primary sources also offer direct reporting on Agilent's decision to sell its stake in Lumileds and the reasons behind the sale. Each of the following four sections is organized chronologically so that the reader may place in time developments in Lumileds' history.

3.5.2.1 Technical progress: New product releases and performance improvement recognitions

Lumileds' early history capitalized on HP's success in entering the automotive lighting product by further developing the red, orange, and yellow LEDs' performance but also sought to take the firm's technology in slightly new directions. For example, Lumileds sought to introduce LED streetlighting as an expansion beyond just automotive lighting (Toupin, 1999). In addition to automotive taillights, Lumileds introduced in 2001 LED products for emergency services supplies firm EP911, including lightbars for police squad cars (Stockton, 2001). In 2000, Lumileds announced that it had achieved a record luminous efficacy (lumens per watt) with its orange-red LEDs of 100 lumens per watt. This efficacy exceeded conventional fluorescent tubes and was achieved much earlier than the industry expected ("Tech Briefs," 2000). Lumileds was reported

in 2000 as having improved efficacies of LEDs through a novel die formations called the truncated inverted pyramid (S. Bush, 2000). Lumileds' own George Craford noted that the red LED, the first LED technology to enter high-brightness applications, has increased its brightness 30-fold per decade and decreased its cost-per-lumen 10-fold per decade. The report mentioned an LED industry norm for LED brightness improvement - similar to the Moore's Law for integrated circuit performance – in which red LEDs were expected to double in brightness every 18 months (Mills, 2001).

Beyond building on HP/Agilent's experience with red, orange, and yellow LEDs, however, Lumileds also sought to expand the performance of other colors – notably green and blue. In late 2000, Lumileds reported having achieved the brightest blue LED product for sale at the time ("Blue LEDs brighten up," 2000). In March 2001, Lumileds also reported achieving record blue LED "wall-plug efficiency" of 25%, surpassing the prior record of 22% (DeMeis, 2001). In early 2001, Lumileds indicated a major breakthrough in its blue and green LED products that Lumileds expected to serve as a major stepping stone toward using LEDs for general illumination (i.e. lightbulbs). Lumileds announced that it had doubled the brightness of its AlInGaN blue and green LEDs, which enabled twelve of Lumileds' new LEDs blue and greento do the work of 180 conventional LEDs ("Double-brightness AlInGaN LEDs," 2001).

The goal of pursuing blue and green AlInGaN LEDs was to combine them with red-orange LEDs in pursuit of a white-light LED product, however. In summer of 2001, Lumileds revealed its new high-brightness white LED product line ("Lumileds launches high-brightness LEDs," 2001). Lumileds branded its new high-brightness white-light LED products under the trademark name "Luxeon," and at the 2001 LightFair conference and expo Lumileds revealed three Luxeon products:

- Luxeon Star, which provided a white light source but no optical components to manage or enhance the light
- Luxeon Ring, which came as 6 or 12 Luxeon light sources and optics to deliver 194 lumens of white light
- Luxeon Flood, which came as a small board of many Luxeon sources delivering 324 lumens of white light

In 2001, Lumileds sought to capitalize on its new high-brightness white LEDs and signalled that it soon would penetrate a new market with its white LED products – that of backlighting Liquid Crystal Displays (LCDs). LumiLeds announced that its new white-colored, high-brightness Luxeon LEDs could be used in the place of the incumbent technology, cold-cathode fluorescent lamps (CCFLs), with many advantages such as increased durability and longer life (“High-flux LED backlights for LCD displays,” 2001). To temper expectatinos about the advantages soon to come from LEDs, Lumileds CEO Mike Holt sought in an April 2001 article to set some realistic boundaries on what LEDs could accomplish in the near-term, what challenges LEDs would need to overcome before becoming adequate for replacing conventional lightbulbs, and when that would happen. Holt expected that LEDs would only suitable for lightbulb replacements after 10 to 15 years of R&D and – importantly – after filling other niche applications in the meantime. Holt expressed concern that many technical accomplishments with LEDs to-date had been achieved at low currents, which masked how well LEDs would perform at typical high-current applications such as general illumination. By this point, the efficiency losses LEDs exhibited at high current were well known, and Holt reminded the industry that these efficiency losses and other technical challenges needed to be overcome before LEDs could “beat the bulb.” In the meantime, Holt laid

out strong optimism for LEDs to begin featuring strongly in applications for automotive lighting and LCD and mobile phone display backlighting (Holt, 2001).

After Holt outlined these expectations for LED product performance in 2001, the year 2002 saw new releases of Lumileds' Luxeon products, affirmation of Lumileds' product life claims, and new applications of Lumileds' old standby, the red LED. In early 2002, Lumileds announced a new white-light LED assembly called the "LuxeonStar/O" available in many colors for supplying flashlights and bicycle lights (S. Bush, 2002a). On April 15 2002, Lumileds announced its release of the Luxeon 5-Watt, at the time the world's brightest LED light source ("5W LED delivers new benchmark in brightness," 2002, "Lumileds Announces Luxeon 5-Watt, the World's Brightest LED Light Source," 2002). Lumileds later exhibited the Luxeon 5-watt and its record 120 lumen white-light output at LightFair in San Francisco in June 2002 ("World's Brightest LED from Lumileds Lighting Debuts at LightFair in San Francisco," 2002), for which Lumileds was granted the "Best of LightFair 2002" award (Conway, 2002). Moreover, while ability to maintain light output over long periods of operation had been a concern for earlier LED technologies, independent tests performed by Rensselaer Polytechnic scientists confirmed that Lumileds Luxeon products maintained 90% of their light output after being on for 9,000 hours (S. Bush, 2002b). In 2002, Lumileds' high-brightness red LEDs were reported as being implemented in radio tower and television tower flashing lights used to warn low-flying aircraft at night ("Applied Technology: Dialight tower lighting," 2002).

The year 2003 saw national recognition of Lumileds' scientists for their contributions to LED technology, more novel applications, new low-wattage white-light LED products, the release of the industry's first "warm-white" LED, and exciting news of designs to use LEDs in camera phone flashes. In November 2003, Lumileds' Chief Technology Officer George Craford was awarded a

2002 national medal of technology for his contributions to LED research (“President Bush Awards Lumileds Lighting’s Chief Technology Officer Dr. M. George Craford The 2002 National Medal of Technology,” 2003). Alongside Craford, another 2002 medal was also awarded to Nick Holonyak – Craford’s advisor in graduate school. Holonyak created the first LED in 1962, and Craford created the first yellow-emitting LED in 1972 (“IEEE engineers earn national medals of science, technology,” 2003). Lumileds’ blue LEDs achieved a novel niche application in February 2003 when they were reported as appearing in products designed to cure dental fillings (“Literally Bluetooth,” 2003). In summer 2003, Lumileds announced soon-to-be-released 2W-50-lumen and 3W-70-lumen LED products (“Lumileds details 3W Luxeon LEDs,” 2003). In Fall 2003, Lumileds announced the release of “Luxeon-III,” a new generation of white-light LED products lasting for 100,000 hours and providing 65 to 80 lumens of brightness (“Lumileds Introduces Luxeon III, an 80-Lumen Long-Life LED,” 2003). Lumileds announced in August 2003 the firm’s development a reference design for its first LED-based flash for camera phones. Able to produce 72 lumens at distances up to 6.5 feet by using a single Luxeon emitter, the new LED-based flash enabled camera phones to approach digital still cameras in terms of flash capability for the first time (Sullivan, 2003). The brightness of the LED-based camera phone flash also enabled dual use as a flashlight (“Lumileds Releases Reference Design for LED-Based Camera Phone Flash,” 2003). The design was later reported in 2004 as having been implemented, achieving illumination of subjects at 1 to 2 meters with two Luxeon LEDs. Cell phones containing the new Luxeon camera phone flashes were expected for the 2004 holiday season (“Camera-phone flash LEDs illuminate subjects at 1 to 2 m,” 2004). In October 2003, Lumileds was reported as selling the LED industry’s first high-brightness “warm-white” LED. Based on its Luxeon technology, Lumileds’ warm-white LED achieved a warm-toned white light that contrasted the common cool-toned white light of most

white-light LED products to date. Development of a warm-white LED was seen as a key breakthrough as it overcame objections from architects and lighting designers to the cool-white colors dominant in white-light LED products (“Lumileds Ships Industry’s First Warm White LED,” 2003, “Warm white Luxeon LEDs by Lumileds Lighting,” 2004).

2004 marked an unfortunately dark year for product performance, as Lumileds had to undertake great efforts to assuage customers regarding problems with non-LED components of its lighting fixtures made by other firms – firms who were attracted to LED revenues but who lacked experience building the proper components. In 2004, reporting revealed an emerging problem within the LED market and that Lumileds, holding most of the market share, would bear the most burden in resolving. Fittings for many LED lighting products had apparently been made incorrectly by firms recently attracted by the high-brightness LED industry’s growth, and the failure of such fittings was sowing doubt among those who had bought into the new LED technologies. Lumileds Director of Market Development Keith Scott was quoted as saying “So many people are getting involved, and we are at a point where not everybody is doing it right... Architects are getting burned," To combat the issue, Lumileds formed an organization called the Lumileds Lighting Network (“LED companies respond to doubts over fitting quality,” 2004). The Lumileds Lighting Network provided training, certification, and technical support to lighting professionals and gave architects and designers access to suppliers meeting a high standard of quality and having proven their expertise in making LED-based products (“Lumileds Forms Luxeon Lighting Network to Aid Lighting Specifiers in Executing Projects Utilizing LED-Based Illumination Program Enables Manufacturers and Solution Providers to Exploit Exploding Market,” 2004).

Building from this new expertise network, the year 2005 saw brighter times for Lumileds’ technical progress, in which Lumileds and Agilent rolled out new mid-power LED products,

Lumileds reported improved Luxeon performance, and Lumileds received many points of recognition for advancing LED-based technologies. In March 2005, Lumileds and Agilent announced the rollout of their first three mid-power LED products under the new product line brand “Envisium.” The products targeted automotive applications, particularly automobile taillights, turn signals, and mirror turn signals (Roos, 2005). In April 2005, Lumileds reported improvements to its InGaN LEDs, the Luxeon I line, improving light output from 31 lumens to 45 lumens in white, blue, cyan, green, and royal blue color (“Lumileds Touts New Luxeon I High Power LEDs,” 2005). Lumileds also reported improvements to the Luxeon III line, including record-breaking lumens-per-package numbers of 110 for amber, 140 for red and 190 for red-orange (“Lighting firm develops 190 lumen LEDs for use in vehicle stop lights and indicators,” 2005). Lumileds announced in June 2005 that the firm’s Luxeon LCD backlight technology had been awarded the silver prize in the 2004 Society for Information Display/Information Display Magazine competition (“Lumileds’ Luxeon Garners Recognition,” 2005). And finally, reporting in May 2005 credited Lumileds with much of the recent advances in mobile phone technology for displays and camera flashes (Nass, 2005).

After Agilent sold Lumileds to Philips, Lumileds’ scientists still remained confident about the prospects of the company’s LED technological progress. At a conference on optoelectronics in December 2006, Philips Lumileds CTO George Craford forecast that the efficiency of white-light LEDs would soon exceed that of fluorescent bulbs and that cost reductions would soon be accelerating LED adoption for general illumination (“OIDA Annual Forum Promotes Energy and Industrial Optoelectronics Applications,” 2006).

3.5.2.2 Dealings with other businesses: Sales contracts, expansions, new revenues

The early years of Lumileds – 1999 to 2001 – saw the joint venture engaging in multiple new business contracts and expansions of its own lines of business, including receiving new resources from Agilent and Philips, partnering with display-makers, and selling to traffic-light vendors. Agilent expressed high optimism about the future of Lumileds through Agilent's early decisions to allocate its existing facilities. In forming Lumileds, Agilent gave the joint venture control of HP's San Jose fabrication facilities for producing AlInGaP and InGaN LEDs instead of giving the facilities to Agilent's Semiconductor Products Group (Szweda, 1999). After two years of collaborating through Lumileds, both HP and Philips agreed to expand the joint-venture in 1999 through a combined investment that would move the scope of Lumileds beyond automotive taillights. Philips executive VP John Whybrow expressed optimism regarding the future market for LED products: "Philips and HP have had more than two years of successful cooperation in the LumiLeds joint venture...Extending this relationship demonstrates our confidence in the technology applied to an increasing range of applications." ("HP and Philips expand joint venture advance LED adoption," 1999). In 2000, Lumileds entered into a marketing contract with Dialight Corp to offer Lumileds' LED traffic signals at 40% price reductions to increase conversions from conventional signals and reduce payback periods for municipal buyers. Lumileds also formed in 2000 a separate "Components Business Unit" within itself to pursue applications of LEDs toward signage lighting ("Lumileds forms new Components Business Unit," 2000). Menko Deroos, Lumileds' VP of New Business Development, stated that Lumileds had begun negotiations with several display-makers and intended to ramp up production of its new LED-powered LCD backlighting products in to the tens of thousands by the end of 2001 (Chin, 2001). At LightFair 2001, Lumileds also announced an extension of a partnership with backlight manufacturer

WooYoung Co. Ltd of South Korea to enter the LCD and TV markets (“Lumileds launches high-brightness LEDs,” 2001). Business reporting revealed that Lumileds had contracted with a subsidiary of lens-maker Fraen to develop technologies for focusing beams from Lumileds’ Luxeon white-light LED devices, based on combinations of red, blue, and green LEDs. The color of the Luxeons could be adjusted by varying the current driven to each color of LED (S. Bush, 2002c).

Later years saw Lumileds earn more sales contracts for displays, move into new markets such as architectural lighting and automotive headlamps (not taillights), deal with contractions, and partner with national laboratories. In March 2002, Lumileds announced a sales contract it had earned with Mitsubishi to develop and vend LED backlights for Mitsubishi’s LCDs (Szweda, 2002). Lumileds announced in August 2002 that the firm had earned a sales contract with Color Kinetics, maker of color-changing LED-based light fixtures (“Color Kinetics Selects Lumileds’ Luxeon Light Sources for New bColor Fixtures, Citing Luxeon’s Industry-Leading Intensity Per LED,” 2002). Lumileds’ Luxeon LEDs would replace CCFTs in backlighting Mitsubishi’s TFT-LCD products, which would be manufactured by Mitsubishi subsidiary Advanced Display Incorporated (Ball, 2002; “Lumileds’ LED-based Backlight System Will Power TFT-LCD Modules for Mitsubishi Electric, Offering Key Benefits for Monitor Manufacturers,” 2002). In December 2002, Mitsubishi announced plans to release the Luxeon-powered TFT-LCD products in 2003 (“Mitsubishi Electric Announces Three LED-Based TFT-LCD Modules Powered by Lumileds’ Luxeon Technology, Scheduled for 2003 Release,” 2002). In 2003, broader contractions in its telecommunications product markets led Agilent to close or relocate certain facilities, with Lumileds remaining as Agilent’s only manufacturer in the US (“Agilent Shifts Sites,” 2003). Lumileds gained positive press in 2003 for releasing Luxeon LED products specifically designed to be fitted onto Amish

buggies, after partnering with a part-Amish-owned solar energy firm (Sadin, 2003; Teresko, 2003). Lumileds also earned sales with Cadillac, as demonstrated by Cadillac's release of the XLR luxury roadster featuring LED taillights and brakelights ("Cadillac's XLR Luxury Roadster Showcases Innovative HID and LED Lighting," 2003). Beyond taillights and brakelights, however, Lumileds' LED products were first reported as appearing in automobile headlights in May 2003. While Lumileds' products had long appeared in automobile taillights and brakelights, Lumileds' products had not yet been featured in headlights until Ford's Model U and Audi's Nuvolari concept cars debuted with LED headlights ("Headlights Go Digital," 2003, "LEDs Light the Way for New Car Headlamp Designs," 2003). In February 2003, LEDs also made their first architectural debut when Lumileds' Luxeon products were used to illuminate Whiteleys Shopping Centre in London. The installation used 2000 LEDs and consumed less than one-third of the energy consumed by conventional light sources for the similar applications (S. Bush, 2003a). In July 2003, Lumileds was reported as being engaged with Sandia National Laboratories in a federally funded collaborative research project to measure the efficiency of quantum dot phosphor technologies for making white light (S. Bush, 2003b).

In 2004, Lumileds formed two separate sales partnerships with its parent firms – one with Philips and one with Agilent. In July 2004, Agilent announced that it would partner with Lumileds in the name of developing mid-power LED technologies. Agilent remained a strong supplier of low-brightness LEDs for telecommunications applications, and Lumileds technology continued to dominate high-brightness applications. The new mid-power LEDs were to be between 200mW and 1W and were to target the automotive, mobile phone, and lighting markets. In the partnership between Agilent and its joint-venture, Lumileds was to provide the LED die and Agilent was to design whole products and provide manufacturing expertise. Mid-power LED products from the

new partnership were expected to be delivered in Q4 2004 (“Agilent Technologies and Lumileds Lighting Announce Agreement to Co-Develop New LEDs,” 2004, “Around the Circuit: Industry News,” 2004; S. Bush, 2004b). In addition to Agilent’s partnership with Lumileds, Philips also partnered with its own joint-venture. In November 2004, Philips and Lumileds announced a partnership to develop modular LED products for the automobile industry. Reporting named Philips as the world’s leader in automotive lighting products, and it was to be the specialty division Philips Automotive Lighting who would provide design, development, and integration capabilities to the new partnership. Lumileds was to provide the already popular Luxeon LED products and related expertise (“Lumileds Lighting and Philips Announce New Partnership,” 2004).

Later years saw Lumileds products featured in automobile running lights, expanding further into display markets through Mitsubishi partnerships, expanding its production capacity, and being hailed as a money-maker by financial analysts. In January 2004, reporting revealed that, for the first time, high-brightness LED products would be used as automobile daytime running lamps in the Audi A8 W12 model. The lamps, using Lumileds’ Luxeon products, were manufactured by the German firm Hella, who expressed optimism about the future of high-brightness LEDs despite European regulations preventing their use in certain automobile lights. Hella claimed to have initiated discussions with European regulators to get the rules changed (S. Bush, 2004a). Capitalizing on its successful contracts with Mitsubishi for developing LED-based LCD backlighting technologies, Lumileds announced in March 2004 that it had developed and released a stand-alone, ready-to-use LCD backlighting technology called “Luxeon DCC.” Rather than purchasing Lumileds’ time and expertise to design specialty Luxeon-powered LCD backlights, LCD makers could now simply order a Luxeon DCC for easy integration into their LCD designs (“Lumileds Releases the First Ready-to-Use RGB LED Light Sources for Backlights,” 2004,

“NEC-Mitsubishi’s LED Backlit LCD Display,” 2004). Mitsubishi debuted new Luxeon-powered TFT-LCDs from the Lumileds booth at the Society for Information Display conference in May 2004 (“NEC-Mitsubishi Electronics Display Launches Its First LED Backlit LCD Display at SID 2004,” 2004). To meet growing demand for its Luxeon LEDs, Lumileds announced in May 2004 that it would be tripling its Luxeon production capacity by opening a new 200,000 sqft manufacturing plant in Malaysia (“Lumileds to Open New Plant in Malaysia, Tripling Production Capacity for Luxeon LEDs,” 2004). Finally, at a conference call on Q3 2004 performance, Philips executives reported that the Lumileds joint-venture with Agilent “again had excellent performance in sales and earnings and cash flow” (“Event Brief of Q3 2004 Royal Philips Electronics Earnings Conference Call - Final,” 2004).

The final years of Agilent ownership and early post-Agilent period saw Lumileds partnering with distribution firms, earning further sales from Mitsubishi, continuing its work on mid-power LEDs, and continuing to be hailed as a money-maker by financial analysts – *after* the split with Agilent. In May 2005, Lumileds announced a joint venture with product distributor Future Electronics that would capitalize on the success of the Lumileds Lighting Network. Called “Lumileds Future Electronics,” the joint venture would provide several services to third parties including Luxeon product assembly, design of lighting systems, new custom optical products, technologies for managing heat and optimizing power usage, and technical support. Moreover, Lumileds Future Electronics partnered with several firms within the Luxeon Lighting Network to expand the firms’ services using trusted LED industry suppliers (“Lumileds Joint Venture Delivers Luxeon-based Products,” 2005). Mitsubishi announced in March 2005 that it would release a pocket-sized projector later that summer and that the projector would make use of Lumileds’ Luxeon LEDs for lighting (Sauer, 2005). Reviews of Mitsubishi’s Pocket Projector were mixed, but the reportedly

device performed well in dark or low-light conditions (Jantz, 2019). After Agilent's sale of Lumileds, Lumileds continued work on the Envisium line of mid-power LED products through a partnership with Avago Technologies ("Avago Technologies' Envisium family of LEDs receive EE Times' ACE ultimate products of the year award," 2006). Finally, At a conference call to review Philips' Q2 2006 financial performance, Philips representatives noted that Lumileds had grown sales 22% above Q2 2005, which itself had been quite high. Philips representatives expressed optimism for future margins (returns) on their lighting operations, including Lumileds ("Q2 2006 Royal Philips Electronics Earnings Conference Call - Final," 2006)

3.5.2.3 Patents: Licensing, disputes, litigation, and risk

While Lumileds earned patent licensing revenues through multiple separate contracts, Lumileds' history saw multiple patent disputes – some of which were inherited from HP/Agilent and most of which concerned die-makers based in Taiwan and China, In October 2001, Lumileds successfully settled a lawsuit it had filed against United Epitaxy Corporation of Taiwan (UEC) for patent infringement. The settlement awarded Lumileds new income from significant patent licensing fees and royalty payments in exchange for allowing UEC to produce device components similar to a window for improving luminous output from LEDs that HP had patented and Lumileds had inherited ("UEC settles lawsuit - licenses Lumileds' T/S LED patents," 2001). Business reporting in 2002 revealed that Lumileds and Nichia had settled a patent dispute with a cross-licensing agreement for white-light LED technologies (S. Bush, 2002d; "LED companies achieve IP cross-license accord," 2002, "Major LED companies Nichia, Lumileds sign cross-licensing deal," 2002). Nichia and Lumileds announced another cross-licensing agreement in February 2003 ("Progress on display," 2003).

Shortly after news of its camera phone flash design, Lumileds filed suit against Epistar for infringing Lumileds' patents on its AlGaInP LED products. Lumileds had earlier filed suit against Citizen Electronics Ltd. and its subsidiary Cecol, Inc. for importing and selling the infringing Epistar products, but those claims were settled separately from the Epistar case ("Lumileds Sues Epistar for Patent Infringement," 2003). In August 2003, Lumileds announced a successful license of several of its AlInGaP technology patents to Shin-Etsu Handotai in exchange for undisclosed royalty revenues ("Shin-Etsu Handotai Obtains License Under Lumileds Patents," 3AD). In July 2004, Lumileds and Epistar settled the earlier lawsuit brought about by Lumileds for infringement of Lumileds' AlGaInP LED technologies. Lumileds granted Epistar a license to practice some of Lumileds' patents, but financial terms of the agreement were not disclosed ("Lumileds and Epistar Settle Lawsuit," 2004).

In August 2004, reporting revealed that Lumileds had earned an R&D contract from US Display Consortium to develop LED products for projectors. The \$2 million R&D project was to be cost-shared equally between Lumileds and US Display Corporation ("Also in the news...", 2004). In February 2005, Lumileds announced a forthcoming advisory regarding the making of mirror substrate LED products. Lumileds signalled that it believed many in the LED industry were infringing on the company's patents, warning industry members that both LED users and LED makers have the obligation to avoid infringing Lumileds' patents (Mills, 2005).

In April 2006, Lumileds and Toyoda Gosei announced a major patent cross-licensing agreement. Toyoda Gosei continued to hold patents on low-power blue LEDs, while Lumileds held patents on high-power blue LEDs. The two firms agreed to allow each to use the other's patents, granting each greater freedom to explore new designs and possibilities for advancing LED technology

(“Philips Lumileds Lighting and Toyoda Gosei Ink Pact to Share LED Patents,” 2006, “Toyoda Gosei and Philips Lumileds Share LED Patents,” 2006).

3.5.2.4 The LED market: expected future growth and interactions with business cycle

Throughout the entire history of Agilent’s part-ownership of Lumileds, the market for Lumileds’ products was always forecast to be growing strongly. In 1999, Semiconductor market research firm Strategies Unlimited forecast that the market for high-brightness LEDs would grow by \$1 billion in five years (“Strategies Unlimited Announces Program for Feb. 10-11, 2000 Conference On Business Opportunities in Advanced LEDs,” 1999). In 2000, Strategies Unlimited was reported as forecasting high-brightness LED market growth of \$2.3 billion in 1999 to \$3.3 billion in 2003 (“LED market lights up,” 2000).

Reporting on the Intertech LED-2000 conference on November 13-15 2000 in San Mateo, CA expressed strong confidence in future growth of the market for LEDs and claimed that Agilent led other suppliers in market share. The report lists several categories of new applications expected to create opportunities for new LED sales growth, including “traffic lights, automotive brake signals, instrument displays, video displays, airport runway, hazardous lighting, and exit signs” (Mills, 2001). At the conference, Stan Brudele of Dataquest forecast annual sales of optoelectronic semiconductor devices to grow from \$6 billion in 1999 to \$12 billion in 2004. Among other optoelectronic semiconductor devices, Brudele’s presentation forecast growth in annual LED sales to increase from \$1.5 billion in 1999 to roughly \$2.5 billion in 2004 (Mills, 2001). Figure 5 provides data used in Brudele’s presentation.

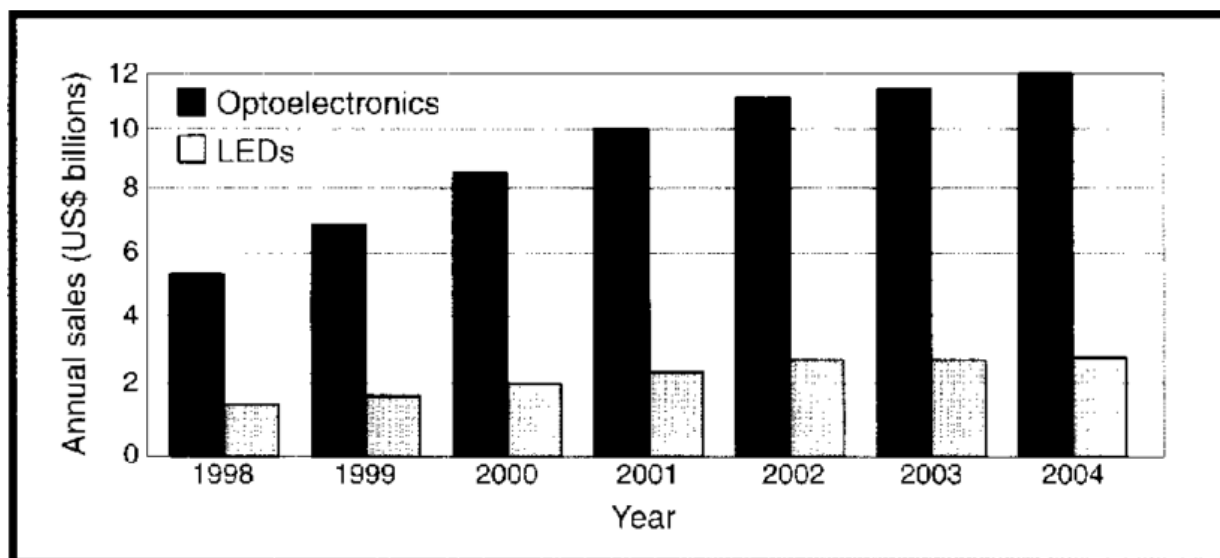


Figure 5: Forecast market growth for LEDs and other optoelectronic semiconductors.
Source: (Mills, 2001)

Brudele's presentation also provided a leaderboard of the top firms supplying LED lamps and displays by 1999 sales, shown in Figure 6. In this ranking, Agilent claimed the top position with 1999 LED sales totalling \$284 million, a full \$60 million over second-place firm Stanley (Mills, 2001).

| 1999 sales (US\$m) | |
|--------------------|-----|
| Agilent | 284 |
| Stanley | 220 |
| Infineon | 216 |
| Mitsubishi | 158 |
| Rohm | 153 |

Figure 6: Market leaders in the sales of LED lamps and displays. Source: (Mills, 2001)

The Intertech conference report's coverage of new firms entering the LED market further underscored the expected growth potential for LED sales. The report listed several recently emerged LED suppliers such as the firms Mingstar, Kingbright, Ledtech, Everlight and Lite-On. The report also mentioned that, beyond Lumileds, other LED-focused joint ventures had been formed between major lighting suppliers and smaller semiconductor firms. The report named the General-Electric-and-EMCORE partnership called GELcore and the Osram-Sylvania-and-Infineon partnership called Osram Optoelectronics as two other joint ventures indicating major lighting firms' interest in the potential LED market shares. The report further underscored major firms' expectations for strong future LED sales growth by mentioning Uniroyal Corp's purchase of Sterling Semiconductor, a cooperative agreement between Uniroyal and EMCORE, Uniroyal's LED-focused start-up NovaLux, and Toyota's 41% stake in LED manufacturer Toyoda Gosei (Mills, 2001).

LED growth even survived economic downturn in the early 2000s and was expected to continue. Through 2001's economic downturn, which severely impacted many technology firms, Strategies Unlimited forecast LED sales to grow by \$400 million to a total of \$1.6 billion. Strategies Unlimited's president John Day explained that while the economic downturn had slowed cell phone sales and with it the sales of cell phone's LED components, LEDs' other markets remained strong. Day explained that car sales in particular, which continued to drive LED sales for automotive brakelights and taillights, were not affected by the downturn, and LEDs' presence in many consumer goods helped the lighting technology continue thriving amidst the economic struggles of the early 2000s. Moreover, LED prices were expected to continue declining at a rate of 10% per year ("LED outlook favors buyers," 2001).

In Summer of 2002, Strategies Unlimited released forecast the high-brightness LED market to grow to \$6 billion in sales by 2006. Strategies Unlimited forecast \$1.6 billion in high-brightness LED sales by the end of 2002 and forecast high-brightness LED prices to fall 10-15% through 2002. Strategies Unlimited's Bob Steele pointed to backlights for LCDs in cell phones as a major driver of new LED sales growth (Chin, 2002; "LED tags fall despite growing market demand (Optoelectronics)," 2002). In a 2002 interview, CEO of Agilent Ned Barnholt stated that Lumileds' white light technologies needed another 10 years to get costs comparable to fluorescent lighting technologies. Barnholt mentioned that most traffic signals had converted to SSL and that the automobile taillight business was still strong. The general economic depression of the early 2000s had given Agilent some market growth in industries that were depressed, but industries that boomed in the early 2000s were dominated by small start-ups and edged Agilent out (Sperling & Chappell, 2002). In January 2003, Strategies Unlimited's Robert Steele forecast steady improvement in LED technology performance and price through the remainder of that year (Steele, 2003).

In March 2004, the LED lighting market was forecast to grow to \$5 billion in annual sales by 2007 ("Lumileds Forms Luxeon Lighting Network to Aid Lighting Specifiers in Executing Projects Utilizing LED-Based Illumination Program Enables Manufacturers and Solution Providers to Exploit Exploding Market," 2004). Later, a 2005 report from firms NanoMarkets and CIR forecast the market for high-brightness LEDs and new ultra-high brightness LEDs to grow from sales of \$5 billion in 2006 to sales of \$11 billion in 2010 sales and to sales of \$17 billion in 2013 ("High-Brightness LED Market to Reach \$10.8 Billion by 2010, According to New Report," 2005).

Strategies Unlimited was reported in 2005 as having released new predictions of the future size of the high-brightness LED market. Strategies Unlimited forecast the market to grow to \$7.2 billion

in sales by 2009, almost doubling from 2004 sales of \$3.7 billion – see Figure 7. Strategies Unlimited also calculated the total portfolio of LED uses for 2005, revealing the dominance of mobile phone applications – shown in Figure 8. Rensselaer Polytechnic University’s Lighting Research Council’s Director of Solid-state Lighting Research Nadarajah Narendra spoke of a “global roadmap” that forecast the efficiency of LED products to reach 150 lumens per watt by 2012 (Costlow, 2005).

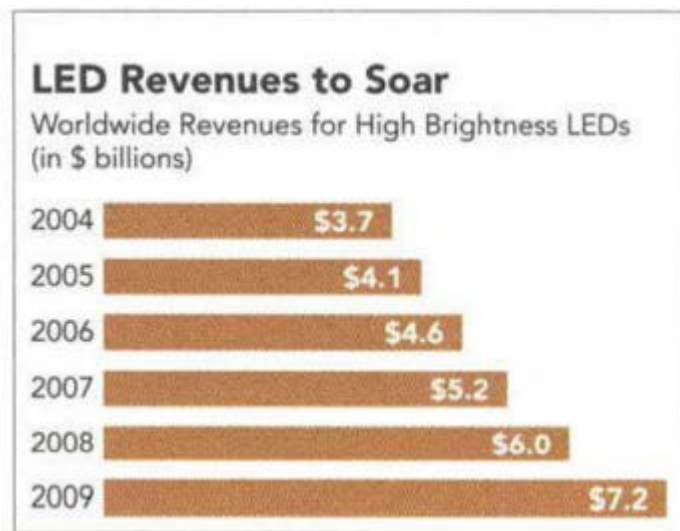


Figure 7: Forecast of high-brightness LED market’s sales revenues for 2004-2009, as calculated by Strategies Unlimited in 2005. Source: (Costlow, 2005)

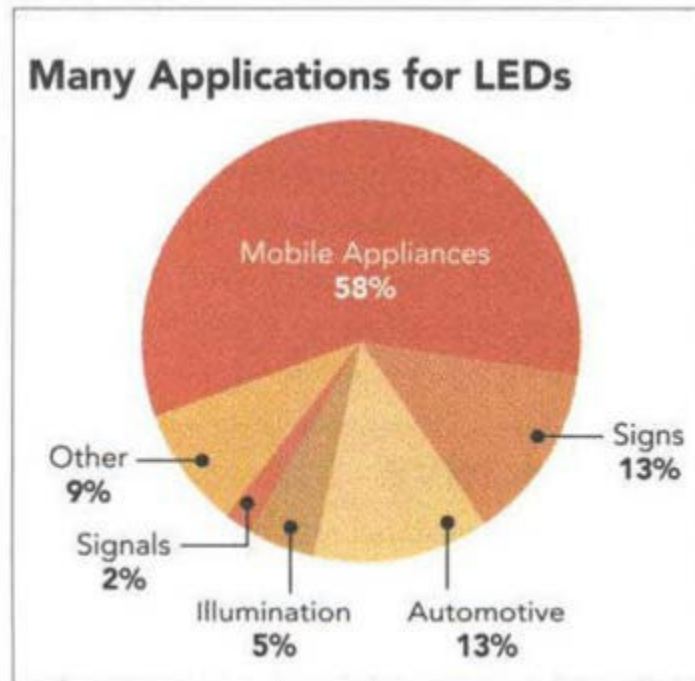


Figure 8: Applications for high-brightness LED products in 2005, as calculated by Strategies Unlimited. Source: (Costlow, 2005)

In August 2006, Strategies Unlimited released its forecast that the LED market would grow to \$4.2 billion in sales by the end of 2006 and would grow to \$8.3 billion by 2010. Strategies Unlimited also forecast LED product costs to decline by 10-15% over 2007 due to “tremendous overcapacity in Asia” (“LED market brightens; tags fall,” 2006).

3.5.2.5 Direct reporting on Agilent’s decision to sell Lumileds

On August 15 2005, Agilent announced that it would sell its stake in Lumileds to Philips. The announcement made it into the pages of the Wall Street Journal, who characterized the sale as part of a series of steps in favor of Agilent’s core test and measurement business (Tam, 2005). A conference call on Q4 earnings revealed that Agilent expected to earn \$1 billion from the sale of Lumileds (“Q4 2005 Agilent Technologies Inc. Earnings Conference Call - Final,” 2005). In

October 2005, Lumileds was reported as having sold its 47% stake to Philips for \$950 million plus \$50 million to repay Lumileds for cash borrowed by Agilent. While Lumileds employees would continue to own 3.5% of Lumileds, Philips now held a 96.5% stake in Lumileds. Lumileds was reported as having had \$324 million in revenue and \$83 million in profits from October 2004 to October 2005 (Overton, 2005). Agilent was reported as planning to return proceeds of the sale to its shareholders through a share repurchase program to commence immediately upon the sale (“Agilent Technologies to spin off SOC and memory test businesses,” 2005). At the same time as the Lumileds sale, Agilent was reported as planning to sell its semiconductor products group (SPG), its SOC business, and its Memory Test business. Signaling the intent behind the planned divestitures, an unnamed Agilent executive was quoted as saying “We believe the decisions we made today will allow our organization to be 100% focused on the measurement market” (McElligott, 2005). Later reporting confirmed the completion of Agilent’s sale of its stake in Lumileds to Philips on November 29, 2005. The reporting specified that the sale of Lumileds, and several of Agilent’s other businesses, were “designed to enhance the company's focus as a pure-play measurement company” (“Agilent Technologies Completes Sale of Its Stake in Lumileds,” 2005). Further reporting noted that “Some engineers [saw the sale of Lumileds] as one company's attempt to return to its roots as a test and measurement instrument maker” (Ohr, 2005).

In a conference call to financial analysts on Agilent’s recent performance, Agilent’s executives expressed great satisfaction with the sale of Lumileds and other of Agilent’s former business lines (“Agilent Technologies Inc. Analyst Meeting - Final,” 2006).

3.6 Conclusions

3.6.1 *Comparing the findings for each hypothesis: which best explains HP's decision to leave Lumileds?*

3.6.1.1 Hypothesis H1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent's lacked Core Capabilities suitable for inter-firm collaboration

Hypothesis H1 appears to hold under the relevant evidence presented. HP/Agilent and Philips appear to have evolved in very different environments and appear to have developed very different Core Capabilities with regard to inter-firm collaboration. While Philips appears to have developed a strong Core Capability of Knowledge-exchange enabling collaboration with outside organizations, HP appears to have developed an innovate-from-within Core Capability focusing on developing its own employee's ideas at the expense of external collaboration. What's more, these Core Capabilities appear to have persisted over each firms' history, as demonstrated by the differences in inter-firm collaboration exhibited by the two firms throughout the 1980s. Review of Agilent's early history finds strong evidence suggesting that Agilent had inherited HP's Core Capabilities despite being a spin-off firm, including those Core Capabilities that hampered external collaboration. Given the evidence, Hypothesis H1 continues to stand as having strong potential for explaining the decision of Agilent to sell Lumileds.

3.6.1.2 Rival Hypothesis R1: HP/Agilent abandoned the Lumileds joint venture because HP/Agilent's expected net returns on SSL technology development fell below HP/Agilent's desired net returns from remaining in the joint-venture

The primary sources reviewed for this chapter make it difficult to assert that Agilent's decision to abandon the Lumileds joint-venture was motivated by low expectations for future returns on SSL technology. Through the various metrics assessed above – technological progress, deals with other businesses, patent-related issues, and forecasted growth for the LED market in general – it seems that Lumileds performed quite well. Throughout the period of Agilent's co-ownership, Lumileds frequently released new products, entered new markets, struck new deals with firms to expand its capacity or sell more of its products, and received wide recognition for its accomplishments. All this occurred against a backdrop of continually forecasted strong growth in the LED market overall. While Lumileds struggled with certain patent disputes, none of the disputes appeared to have been egregiously costly to the firm and many of the disputes were inherited from Agilent itself – thus making it unlikely that Agilent could shield itself from litigation by losing Lumileds. Moreover, the direct reporting on Agilent's decision seems to indicate that Agilent's goal was to re-focus its efforts on its measurement instruments business. Even more convincing is the financial reporting by Philips analysts that Lumileds continued to be a money-maker for the joint-venture's co-owners before Agilent sold its stake, and continued to be a money-maker for Philips with strong expected future growth after Agilent sold its stake.

Given the weight of this evidence, Rival Hypothesis R1 cannot stand. It seems implausible to argue that Agilent sold its stake in Lumileds due to low expected revenues from SSL technology development. All evidence revealed through review of primary sources on Lumileds, Agilent, and Philips indicates that Lumileds enabled Agilent to hold a dominant share in a rapidly growing market and earn additional revenues from patent licenses. No evidence indicates reason to believe Lumileds would be a money-loser or that SSL R&D would not enable Lumileds and its owners to earn future revenues in the LED market.

3.6.2 Synthesis: Organizational Capabilities explain Agilent's sale of Lumileds to Philips

When faced with the question of why Hewlett-Packard's spin-out Agilent abandoned its LED joint-venture with Philips, Nelson and Winter's evolutionary theory of economics provides key explanatory insights. This study examined relevant data on each firm's early history, decision-making routines, and collaboration behavior during the 1980s, finding links between each firm's established decision-making routines (i.e. "Core Capabilities") and each firm's 1980s inter-firm collaboration. The study finds that Nelson and Winter's hypotheses regarding evolutionary economics hold under evidence from the histories of Hewlett-Packard, Philips, and each firm's inter-firm collaboration behavior. Moreover, the study finds that the specific history of Agilent and its Core Capabilities inherited from Hewlett-Packard explain the decision by Agilent to abandon its joint-venture with Philips in 2005.

Having found Nelson and Winter's theory to withstand evidence from the histories of Philips and Hewlett-Packard and to provide explanation for the fate of their joint venture Lumileds, future work could apply the theory to Lumileds' own behavior. What are the Core Capabilities of Lumileds itself? What capabilities did it inherit from Philips or from Hewlett-Packard/Agilent? How did those Core Capabilities impact Lumileds' performance? Since Philips divested Lumileds in 2017, how has Lumileds exhibited its Core Capabilities?

3.6.3 Lessons for policy-making

Policymakers who design policies to affect R&D performed by firms and academics who study R&D performed by firms should care about this chapter because it reveals a key latent factor, Core Capabilities, that affects how a firm performs R&D and whether it will collaborate on R&D with other firms. This chapter highlights how Core Capabilities hampered the collaboration between

two firms, Hewlett-Packard and Philips, on developing new technology for SSL. Hewlett-Packard and Philips were an ideal match for developing SSL technology and assisting SSL innovation because of Hewlett-Packard's expertise in optics and solid-state materials and Philips' expertise in designing and manufacturing consumer lightbulbs. Moreover and more importantly, many policies had been put into place to foster inter-firm collaboration, a major policy shift from the post-World-War-II era in which inter-firm collaboration within the US had been discouraged by policy. Yet despite policies favoring an advantageous case of interfirm R&D collaboration, Hewlett-Packard and Philips collaborated through a joint-venture only a short while before Hewlett-Packard abandoned the joint-venture and SSL altogether. The analysis presented in this chapter reveals that Core Capabilities were to blame for the infringed collaboration between Hewlett-Packard and Philips.

Since this chapter's analysis reveals a factor affecting firms' R&D performance, policymakers and academic researchers focusing on this area should alter their policy designs and research designs accordingly. Policymakers should take assessments of the Core Capabilities of the firms whose R&D they seek to influence and design policies so as to take advantage of – or at least not get thwarted by – firms' Core Capabilities. In a similar manner, academic researchers interested in what drives firm R&D should look further into the Core Capabilities of firms of interest. Researchers should account for a firm's Core Capabilities when estimating the influence of any other factor on the firm's R&D performance. Moreover, publicizing analyses that establish individual firms' Core Capabilities would be of great use to policymakers seeking to design policies influencing those firms' R&D.

CHAPTER 4. PATH-DEPENDENCIES AND PATENT LICENSING: THE US DEPARTMENT OF ENERGY'S COMPULSORY LICENSING POLICY

4.1 Research Question

This chapter seeks to answer the following question: Did the DOE SSL's compulsory licensing policy have a negative impact on patent production among affected leaders of DOE-SSL-funded projects? Through legislation passed in 2005, Congress required the DOE SSL program to solicit input in determining R&D priorities from major lighting industry firms and, in exchange, to give these major firms licensing guarantees to any patents arising from program-funded R&D. To meet this requirement, the DOE SSL program required owners of patents on program-funded R&D to enter into license negotiations only with any member of the group of firms who provided input in determining the program's R&D priorities – a compulsory licensing policy. The DOE wrote that instituting the compulsory licensing policy would help ensure that research funded by the program ultimately resulted in new products introduced in markets (McCabe & Gottlieb, 2006). Prior literature suggests that compulsory licensing policies can reduce researchers' overall patenting, however, which could lead to a reduction in patent licensing and reduction in new product introduction – thus thwarting DOE's expectations of the policy. In particular, some theories articulate a path-dependency affecting researcher patenting in which the history of expropriation and reverse-engineering in an industry determines the degree to which inventors are willing to patent their discoveries. Given the conflict between the DOE's expectation for the policy and the

academic literature, this study seeks to identify the impact of the DOE's policy on affected researchers' patent production.

4.1.1 Origins of the compulsory licensing policy: The Energy Policy Act of 2005's directive and the NGLIA

The Energy Policy Act of 2005 instituted the DOE SSL program's distinctive rules towards issues of intellectual property and patenting. The Energy Policy Act's Section 912(h), "INTELLECTUAL PROPERTY," empowered the US Secretary of Energy to make special requirements of any patented invention whose supporting R&D was funded by the DOE SSL program's grants. In particular, Section 912(h) empowered the Secretary to grant exclusive first rights to negotiations with the patent owner for non-exclusive patent licenses and royalties. Section 912(h)(1) named the members of an Industry Alliance, defined elsewhere as for-profit firms representative of US SSL R&D and manufacturing efforts, as the first-rights recipients. Furthermore, Section 912(h)(2)(A) prohibited the patent owners from licenses negotiations with any non-members of the Industry Alliance, a prohibition to last for one year after a patent's first granting. During the patent's initial year, Section 912(h)(2)(B) requires the patent owner to engage in good faith negotiations with any interested member of the Industry Alliance – preventing patent owners from refusing license negotiation outright. Finally, Section 912(h)(3) granted the Secretary the power to enumerate further undefined terms governing patent licensing "as the Secretary determines are required to promote accelerated commercialization of inventions made under the initiative." (109th Congress, 2005)

To fulfill the authorizing legislation's requirements for an "Industry Alliance," a number of lead firms in the lighting industry joined together to form a group called the Next-Generation Lighting

Alliance (NGLIA). Table 7 provides data on NGLIA membership between 2003 and 2014. As written in the legislation, the NGLIA constituted a diversity of firms with knowledge regarding different parts of the SSL value chain. Firms represented in the NGLIA included both large firms with global manufacturing presences and small firms with niche specialty in the semiconductors industry or in related materials technologies.²⁰

²⁰ According to conversations with PNNL scientists, most of the major firms in solid-state lighting were members of the NGLIA at one point or another.

Table 7: Membership in Next Generation Lighting Industry Alliance, 2003-2014. Source: Wayback Machine research; NGLIA and DOE documents

| Firm Name | Year of firm's membership in Next Generation Lighting Industry Alliance (1=member, 0=non-member) | | | | | | | | | | | |
|-------------------------------------|---|------|------|------|------|------|------|------|------|------|------|------|
| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| 3M | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Acuity Brands Lighting | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Air Products & Chemicals, Inc. | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Applied Materials, Inc. | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| Bayer MaterialScience, LLC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| CAO Group Inc. | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Color Kinetics | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Corning, Inc. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Cree Inc. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Dow Corning Corporation | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Eastman Kodak Company | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| EYE Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| GELCore LLC | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GELcore, LLC | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| General Electric Company | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| GLO USA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Light Prescriptions Innovators, LLC | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| LSI Industries | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Lumileds Lighting, LLC | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Luminus Devices, Inc. | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| Osram Sylvania, Inc. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Philips Electronics | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| QuNano, Inc | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| Ruud Lighting, Inc. | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| Universal Display Corporation | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |

4.1.2 Details of the DOE SSL Program's compulsory licensing policy

The DOE implemented the 2005 Energy Policy Act's requirement for special licensing privileges by first obtaining an exemption to the Bayh-Dole act; and second, instituting a compulsory licensing policy. Passed in 1980, the Bayh-Dole Act (35 U.S.C. 202(a)(ii)) reversed the stakes in patenting federally funded R&D by placing rights to the patent with the funded entity instead of with the federal government and its agencies. As such, the Bayh-Dole Act stood in the way of the US DOE's 2005 Energy Policy Act directive to control the licensing of patents on R&D the program had funded. To circumvent the Bayh-Dole act, the US DOE prepared and published an analysis justifying its exemption to the Bayh-Dole Act on the grounds that, in this circumstance, enforcement of the Bayh-Dole Act would conflict with the act's intent (McCabe & Gottlieb, 2006). This enabled DOE to acquire an exemption to the Bayh-Dole Act under the Act's own rules.

Having obtained the exemption to the Bayh-Dole Act, the US Department of Energy proceeded to institute a form of compulsory licensing policy for the DOE SSL program. Under this policy, any holders of patents based upon research funded by the new SSL program were required to engage in non-exclusive licensing negotiations arbitrated by the US DOE (McCabe & Gottlieb, 2006).²¹ Researchers supported by the SSL program's

²¹ The Department determined that the Exceptional Circumstances Determination would last for 10 years from the date first approved. However, the Department qualified that it would retain the right to end the Exceptional Circumstances Determination if the Industry Alliance were to end the memorandum-of-understanding stipulating the Alliance's collaborative support for the SSL program. In other words, the Department conditioned the Exceptional Circumstances Determination and the guarantee of licenses on the Industry Alliance's continued support for the program. The Department also reserved the right to transfer the Exceptional Circumstances Determination and its license guarantees onto any group that replaced the Industry Alliance if the original Alliance were to dissolve (US Department of Energy, 2006). The NGLIA (the Industry Alliance) and the US DOE have signed a number of memorandums of understanding that have extended the original compulsory licensing provision throughout the life of the DOE SSL program (Risser & Cook, 2010, 2012, 2014).

“Core Technologies Program” (“Core Technologies”), a division of the DOE SSL program dedicated to basic research for SSL products, were allowed to retain title to any patents made from Core Technologies projects. Contrary to the Bayh-Dole Act, however, the EC required that patent-holding Core Technologies researchers would engage in license negotiations with the NGLIA members. Core Technologies researchers could negotiate licenses with only the NGLIA members during the year following the creation of a patent from a Core Technologies project. The EC specified that the terms of the licenses, including royalty payments, were to be “reasonable under the circumstances” (McCabe & Gottlieb, 2006, pp.2). Moreover, the EC required NGLIA members and Core Technologies researchers to negotiate non-exclusive licenses, meaning that more than one NGLIA firm could acquire a license to the patent at stake²². If the negotiations did not produce a license agreement after 9 months, the NGLIA members could file suit against the Core Technologies researchers to compel licensing. The Core Technologies researchers retained title to their patents during the license negotiations. After a year had passed since the creation of the patent, the EC released the Core Technologies researchers from having to negotiate only with NGLIA members and allowed the researchers freedom to negotiate licenses with any party. The EC also recognized that the membership of the NGLIA would change over time as new firms joined NGLIA and old firms left NGLIA. In recognition of fluctuating membership, the EC only allowed firms to negotiate licenses to patents for which Core Technologies researchers had applied during the firm’s membership in NGLIA (McCabe & Gottlieb, 2006).

²² An exclusive license was allowed when only one NGLIA member expressed interest to the DOE in licensing the Core Technologies patent.

4.2 Literature review: Prior findings on patent licensing and patent production

Given the novel patent licensing policy put in place by the US Department of Energy, the analysis begins with a review of prior studies for guidance on the impacts of intellectual property policies in general. This section describes prior studies and their findings on compulsory licensing and patent production.

4.2.1 *Prior studies analyzing patent licensing policies and patent production*

Scholarship on intellectual property policies and researchers' patenting help to guide expectations regarding what the impact of the DOE SSL Program's compulsory licensing policy might have been. Studies of intellectual property policies in general and specific kinds that bear semblance of compulsory licensing policies can help us understand what factors policies seek to affect and the reasoning behind policy design. Of great importance, such policy studies can help us understand the general effects of the policies themselves and what effects we might expect from the DOE SSL Program's compulsory licensing policy. Moreover, studies of patenting behavior in general help us understand what factors *other than* intellectual property policies affect patenting behaviors. Studies of patenting behaviors provide the crucial context of rival hypotheses to the idea that an intellectual property policy alone has impacted patenting behavior in a certain context. Studies of patenting behavior suggest alternative explanations of any apparent patent behavior – suggestions that something other than the policy in question produced the apparent behavior. We must address the alternative explanations exploring the impacts of the DOE SSL Program's compulsory licensing policy. This subsection summarizes selections of prior research into intellectual property policies and general patenting behavior.

Scholarly disposition on the impacts of compulsory licensing has been mixed, with some scholars arguing that compulsory licensing will undermine innovation and technological progress. Some scholars argue that patent-holders will likely receive a lesser reward for the expense endured during research and development if their licensing compensation is dictated by governing bodies. As a result, researchers may be less likely to pursue patents as a means of exploiting their inventions. Less patenting could slow innovation overall by restricting the public disclosure of discoveries provided by the patent system (Epstein & Kieff, 2011). Scholars also point out that the US Supreme Court has many times interpreted the patent provisions of US code as not requiring any utilization of the patent or the knowledge embedded in the patent (Tyler, 2014).

Conversely, other scholars argue that reduced compensation for licensing increases the likelihood that a patent will be licensed and worked into a commercial product that could deliver social benefits. Patent-owners could still earn high returns on low-compensation licenses by investing in patent licensees, and accelerated commercialization of patents could even stimulate innovation by creating greater technological competition (Tullis, 2005; Tyler, 2014; Yosick, 2001). As such, compulsory licensing could maintain or even accelerate the pace of innovation while accelerating societal returns from research and development efforts. Moreover, some cases of compulsory licensing have in the past stimulated greater production of patents (Moser & Voena, 2012), falsifying the assertion that compulsory licensing will always diminish overall patent productivity. FM Scherer's 1977 monograph on compulsory licensing concludes that, while the policy may

disadvantage smaller innovators, the innovation economy would likely not be affected (Scherer, 1977) .

4.2.1.2 Studies of patent production

Scholars have long-studied the production of patents by both firms and individuals, and studies of patenting have shown a handful of key categories of variables to bear relevance. Given the lengthy history of the patent system as a policy, studies of patenting can make use of data from centuries ago (e.g. Moser & Nicholas, 2013). The literature identifies at least eight key categories of factors that influence patenting: Collaborations, Expected Returns, Firm Size, Industry of Innovator, Individual Inventor Features, Internal Firm Features, Government Policy, and Competition. The following paragraphs describe each of these categories in more detail.

While literature recognizes that R&D collaborations between firms accelerate patenting, findings indicate some nuance to the types of collaboration necessary. Firms do appear to produce more patents and increase their overall R&D activity when participating in a collaborative inter-firm partnership (Brouwer & Kleinknecht, 1999). While being in a partnership tends to accelerate patenting, however, the effect does not appear to scale; having a greater number of collaborators does not appear to accelerate patenting in proportion (Fornahl, Broekel, & Boschma, 2011). Instead, the complementarity of knowledge held by two partnering firms seems to do more to accelerate patenting. Having an optimal cognitive distance, i.e. an intermediate level of differences between each firm's core R&D capacities, seems to accelerate patenting. Finally, being located within an

industry cluster seems to accelerate patenting, possibly due to the availability of potential collaborators (Fornahl et al., 2011).

Research finds that patent applicants are also motivated by money. While academic inventors may be motivated to pursue patents for a variety of reasons, the expected royalty payments for licensing a patented technology motivate universities to patent (Baldini, 2011). For corporate inventors, monetary motivations still play a role; however, the distribution of motivation is somewhat nuanced. Small, R&D-intensive firms appear most likely to patent for reasons of extracting royalty payments. Firms in biotechnology, pharmaceuticals, and computing also appear more likely to patent for monetary reasons, as do firms located in the US (de Rassenfosse, Guellec, & de la Potterie, 2008).

When attributing patents to firms, the simple size of the firm affects whether and with what intensity the firm pursues patenting; yet nuance persists in this area, as well. First, large firms in general are more likely to pursue a patent than small firms (Chabchoub & Niosi, 2005; Holgersson, 2013), even after control for the innovative effort of the firm (Brouwer & Kleinknecht, 1999). Among firms that choose to patent, however, being a smaller firm increases the number of patent applications by the firm on average (Brouwer & Kleinknecht, 1999). The existence of small firms oriented around R&D activities in some sectors creates the trend of small firms pursuing patents with more vigor than large firms (de Rassenfosse et al., 2008).

Effects related to the technology used by an entire industry influence the patenting of a given firm or individual within that industry (Brouwer & Kleinknecht, 1999). Literature has established some industries as dominant patent-producers, such as pharmaceuticals and

biotechnology (and chemistry writ-large). Service-based industries, such as marketing, also tend to produce fewer patents. Being in industries that produce a great deal of patents, such as pharmaceuticals and biotechnology, increases the number of patents that a firm produces on average. Not being in a service-based industry increases the number of patents that a firm produces on average (Chabchoub & Niosi, 2005). Similar group-level effects extend to academic inventors, in which the academic inventor's field of research plays a role in determining the academic inventor's patenting (Hussler & Penin, 2012).

Below the field-level and the sector-level, scholars have found several individual-level factors that influence the patent propensities of individual inventors. Among academics, for example, having greater non-university work experience begets greater patenting. Age also increases the likelihood of having acquired a patent due to accumulated discoveries and accumulated knowledge of the patent system (Grimm & Jaenicke, 2012). As with many things in science and knowledge, a Matthew Effect exists for patenting; prior successful technology transfer increases an individual's likelihood of patenting (Hussler & Penin, 2012). An intergenerational Matthew Effect may also exist for patenting, as an inventor's father's patenting appears to increase the patenting of an inventor (Link & Ruhm, 2013).

Certain attitudinal factors influence patenting, but other attitudinal factors have no influence. Having a desire for prestige and reputation or a desire for knowledge exchange increases the likelihood of an individual academic to patent (Baldini, 2011). Conversely, having a positive perception of patenting or being willing to work on patentable research does not affect an individual's patenting (Baldini, 2011).

Finally, an individual's immersion in scientific activity – that is, production and consumption of scientific publications – has a nuanced effect on that individual's patenting. On the one hand, production of scientific publications has no effect on patenting. On the other hand, making a greater number of citations to scientific publications appears to increase an individual's patenting (Suzuki, Gemba, Tamada, Yasaki, & Goto, 2006).

Research finds that the characteristics of the firms in which individuals work also affects the individuals' patenting. The extent to which a firm and its constituents have knowledge of the patent process or have personnel and other resources dedicated to working the patent process increases the firm's patenting (Holgersson, 2013). Similarly, a greater extent of training on how to use the patent system offered by firms increases the patenting of the firms, as well as offering rewards within the firm for patenting (X. Li & Ni, 2012). A greater level of firm's innovation effort or R&D spending also increases the firm's patenting (Perez-Cano & Villen-Altamirano, 2013).

Beyond training, expenditure, and knowledge related to patenting, a more subtle way in which knowledge is treated within the firm influences a firm's patenting. A greater extent to which knowledge is codified increases the firm's patenting (Perez-Cano & Villen-Altamirano, 2013; Perez-Luno & Valle-Cabrera, 2011). When new knowledge is written down, documented, archived, organized, and in other ways made accessible to a firm's constituents beyond those who developed the knowledge, the codification of that knowledge increases. Codification enables constituents of a firm to more easily innovate by building upon one another's knowledge. Codification also augments the positive effect of R&D expenditure by the firm upon patenting (Perez-Luno & Valle-Cabrera, 2011).

Beyond provisions for IP, research finds other government actions that have effects on patenting. Subsidies to single firms seem to have little effect; yet in tandem with the literature on research collaboration, subsidies to multiple firms engaged in research partnerships increases patenting (Fornahl et al., 2011). Also, policies that restructure, dissolve, merge, or otherwise overhaul major patent producers – such as large corporations or government laboratories – decrease patenting (Vanecek, 2008).

The influences of competition upon patenting are complex, numerous, and nuanced. Knowledge disclosure risk lies at the forefront of competition-based effects upon patenting. When inventors acquire patents, they disclose the workings of their innovations in ways that could be useful to competitors seeking to innovate in similar ways. An increased perception of high disclosure risks reduces patenting (Duguet & Kabla, 2000; Heger & Zaby, 2013). Much of the perception of risks from disclosure hinges on the inventor's understanding of how useful the disclosed information could be to competitors (Heger & Zaby, 2013). The exclusionary power of patents can balance the risks of disclosure, however; moreover, the exclusionary power may become salient when a firm faces threats from imitators. Elevated competitive threats from imitators increase patenting (de Rassenfosse et al., 2008; Hu, 2010). Barriers to entry into the firm's market decreases patenting, however, because barriers lessen the threats from would-be competitors regardless of whether they acquire the inventor-firm's knowledge (Heger & Zaby, 2013).

Beyond knowledge-protection and exclusion, however, competition influences inventor's decisions to acquire patents in contexts having more to do with negotiations. Where inventors desire to improve their negotiating positions in technology transfer negotiations, patenting tends to increase (Duguet & Kabla, 2000). The exclusionary power of patenting

acts as leverage for the firm to exploit more from their negotiating counterparts. Conversely, when an inventor-firm's desire to avoid lawsuits increases, patenting increases as well (Duguet & Kabla, 2000).

4.2.2 *Path-dependency and patenting: The Theory of Appropriability Regimes*

Teece and others provide a path-dependent explanation for the role that government policies and actions toward innovation efforts affect firm and individual patent production. In particular, Teece emphasizes the degree to which the patented technology could otherwise be easily reverse-engineered, imitated, and thus appropriated. An overarching theme of literature is that a government's offering of stronger intellectual property (IP) protection and IP enforcement increases patenting (Dechezlepretre, Glachant, & Meniere, 2013; Machlup, 1958). Frameworks by Teece and others posit that the offering of IP protection and enforcement increases inventor's perceptions of favorable "appropriability conditions," i.e. environmental conditions in which benefits from patenting can be derived (Teece, 1993, 1998). The increase in perceived appropriability in turn motivates the inventor to pursue a patent. Appropriability conditions influence much of the expected returns on patent licenses via royalty payments (Cohen, Nelson, & Walsh, 2000; Teece, 1998). Teece's framework offers the concept of "observability-in-use" to explain competitive threats; the greater degree to which the knowledge embedded in an innovation can be observed in the innovation itself, the greater the imitation threat (Teece, 1998). Of most importance, Teece's Appropriability Regimes framework supports this assertion in hypothesizing that relaxing intellectual property (IP) protections through policies such as compulsory licensing reduces innovators' pursuit of patents (Teece, 1993, 1998).

4.3 Hypothesis and rival hypotheses on the effects of the DOE SSL's compulsory licensing policy on patent production

Much of the prior work on patent production gives a clear impression that scholars expect any policy introducing restrictions on the use and licensing of patents to discourage researchers from pursuing patents.

4.3.1 Hypothesis H1: The compulsory licensing policy decreased patenting among inventors whose work was funded by the DOE SSL program

Moreover, from the work by de Rassenfosse, Guellec, & de la Potterie (2008) and their finding on the patent-centricity of some smaller firms, we can add a corollary hypothesis:

4.3.2 Hypothesis H1a: The compulsory licensing policy reduced the patenting of researchers at smaller firms more than the patenting of researchers at larger firms.

From other findings on patenting behavior, however, we can derive rival hypotheses of the policy's effects on funded researchers' patenting behavior. In particular, the works of Moser & Voena (2012) and Scherer (1977) indicate that compulsory licensing will not affect patenting and could even increase patenting. This gives us one rival hypothesis:

4.3.3 Rival hypothesis R1: The compulsory licensing policy had no effect on inventors whose work was funded by the DOE SSL program

The literature reviewed also identifies several intervening inventor-level and firm-level factors that influence patent production. While it is likely impossible to develop a hypothesis that accounts for all of these factors, one factor found to influence patenting

deserves its own hypothesis – that of a researcher’s years of experience. Since Grimm & Jaenicke (2012) find that age and experience increase the number of patents a researcher is likely to produce, we can add a second rival hypothesis. With this second rival hypothesis, instead of a contrary prediction, this hypothesis offers a conflating explanation as the grounds for disconfirming other hypotheses:

4.3.4 Rival hypothesis R2: Any observed differences between researchers subject to the compulsory licensing policy and researchers not subject to the compulsory licensing policy are due to age differences between the two groups and not to the effects of the compulsory licensing policy.

Finally - from Teece’s Appropriability Regimes framework, we can derive hypotheses on the impact of a compulsory licensing policy on affected researchers’ patenting behavior. Important to note is that compulsory licensing amounts to a relaxation of IP protection. Because the government entity offering IP is now compelling the inventor to share rather than exclude certain others from use of the patent, the government is relaxing the IP protections. In Teece’s framework, this increases the inventor’s technology’s appropriability (Teece, 1998). Increasing appropriability decreases the inventor’s incentive to file a patent, since the patent no longer empowers the inventor to keep others from appropriating the patented technology.

4.3.5 Hypothesis H2: The compulsory licensing policy decreased patenting by researchers facing high Appropriability Regimes more than it decreased patenting by researchers facing low Appropriability Regimes in the industries of the researchers’ respective firms.

4.4 Methodology

To test the hypotheses derived from our literature review and model of patent production, we compare patent productivity at a given point in time between researchers funded by the DOE SSL program and researchers that the program hadn't yet funded. Because program funding subjects a researcher to the compulsory licensing policy described in earlier sections, program funding represents a change to the researcher's Appropriability Regime. Measuring changes in productivity before and after funding for a given researcher could measure the impact of the Appropriability Regime change. Our model derived from the literature suggests that the Appropriability Regime change would have discouraged researchers from patenting. As such, the operationalization of the effect of the compulsory licensing policy is that, at a given point in time, we expect the researchers who have not yet been funded to be producing more patents than the researchers who have been funded.

4.4.1 *Advantages of comparing patent productivity between sampled researchers*

Comparing patent productivity within a group of researchers that were all funded but who were funded at different points in time enables control of key factors, other than the Appropriability Regime, that may have influence patent productivity. By the term "key factors," this methodology refers to rival hypotheses, i.e. alternative explanations for any findings confirming any of the hypotheses being tested. Specifically, studying only researchers who were eventually funded by the program controls for any variables that may have influenced both patent productivity *and* the US Department of Energy's decision to fund the selected researchers. Social scientists refer to the effects of factors falling into

both categories as “selection effects.” Assume, for example, that the Department of Energy had chosen to fund researchers that somehow inherently produce fewer patents than is average for researchers. If we were to compare funded researchers to non-funded researchers, any effect of the compulsory licensing program and the associated Appropriability Regime change would be conflated with the inherent productivity of the selected researchers. In other words, we would be severely challenged in determining whether any difference in patent production observed between eventually-funded researchers and never-funded researchers was due the compulsory licensing policy or to the fact that the US Department of Energy had chosen low-patent-productivity researchers. Conversely, because our study compares patent productivity only among researchers that were eventually chosen by the US Department of Energy, we would in this hypothetical example be comparing low-patent-productivity researchers to other low-patent-productivity researchers. Any difference observed could therefore more arguably be attributed to the compulsory licensing policy’s Appropriability Regime change and not to the US Department of Energy’s proclivity toward choosing low-patent-productivity researchers. The approach to measuring and comparing researchers’ patent productivity requires data on what patents each researcher produced and data on the researchers themselves, and this study collects both kinds of data. The next two sections describe the study’s data collection processes.

4.4.2 Gathering data on patents produced by DOE SSL PIs

For data on the number of patents produced by each funded researcher, I use the Fung Institute’s set of patents disambiguated by inventor. Researchers at the UC Berkeley Fung Institute used a patent disambiguation algorithm to process US Patent and Trademark

Office (USPTO) records into a structured database (G. C. Li et al., 2014). The database includes a table containing each USPTO-granted patent assigned to a unique inventor ID that the researchers constructed using a sophisticated algorithm to disambiguate inventors from the USPTO records. US patent grant records frequently list the name of a single inventor in a variety of forms; for example, if this author were to be granted multiple patents, one might expect to see some patents granted to “Alexander M. Smith” and other patents granted to “Alex Smith.” The problem clearly becomes compounded when one considers the possibility of a patent being filed by a different person with the same name, or a sufficiently similar name – consider an “Alexandra Smith,” e.g.. Such small differences in recorded names create major problems for researchers seeking to uniquely identify each inventor from a set of patents, so the Fung Institute’s inventor-disambiguated patent database provides huge advantages to studies using unique inventors as a unit of analysis, such as the present study.²³

The inventor-disambiguated database alone does not solve all problems, however, as it remains necessary to identify each inventor from the DOE SSL program’s list of funded principal investigators within the Fung Institute’s database. For this purpose, I first acquire via email exchange the list of funded principal investigators via an email exchange with Navigant Consulting, the consultancy hired by the DOE to administer portions of the DOE SSL program. Next, I research each funded principal investigator via Google searching for information on the professional background of each funded principal investigator, focusing on CVs posted to the internet or LinkedIn profiles as primary sources.²⁴ Using the

²³ For further details on the Harvard/Fung Institute disambiguated patent database, consult Li et al., 2014.

²⁴ This methodology follows that used by Melkers, Panomariov, and other premier researchers in bibliometrics.

professional background information gathered, I then query the Fung Institute's table of patents disambiguated by inventor (downloaded via the file "grant_inventor.tsv") for the first and last name of each funded principal investigator.²⁵ I cross-reference the query results with professional background information and identify the Fung Institute data table's unique inventor ID number representing a funded principal investigator. Using the list of all Inventor IDs representing funded principal investigators, I then use SQLite3 to query the Fung Institute's data table for all patents granted to Inventor IDs in the list. This forms the initial data set.

Since I acquired Navigant's list of funded principal investigators in 2015, it only lists funded investigators through 2014. To balance the observations before and after the 2005 implementation of the DOE SSL program's patent licensing policies, I set the timeframe of my analysis as 1996 to 2014 – providing 9 years' worth of observations before and after 2005.

Because the Fung Institute's data table does not include the year of the patent, I cross referenced USPTO data from the USPTO's PATFT online database.²⁶ Patent numbers are chronological, so I identified the first and last patent of each year from 2000 to 2015 and then used SQLite3 to assign a year to all patents in the initial data set. I then use SQLite3 to sum all patents for each investigator-year, making the unit of analysis the investigator-year and the dependent variable the sum of patents granted to that inventor.

²⁵ I used MS Access, Python's SQLite3, and SQLite Management studio to perform this task. Each software program functions on a SQL foundation and returns the same results, but the interface and ease of using each software program varies with, among other things, the computer platform from which one is working.

²⁶ <http://patft.uspto.gov/netahtml/PTO/search-adv.htm>

4.4.3 *Gathering data on DOE SSL PIs themselves*

Given that many patent production factors identified via the literature review relate to either the individual inventors or to the organizations employing inventors, I also gather data on the professional backgrounds of each funded principal investigator. Since I have already gathered data on the principal investigators for purposes of identifying them in the Fung Institute's database, I use the same data gathered to identify features of each principal investigator and the organizational affiliation history of each principal investigator. I drop from my sample any principal investigators whose data do not contain information on the investigator's organizational affiliation history, reducing the number of investigator-year observations in my dataset. For the remaining investigators, I use a combination of manual data entry and automated web-scraping techniques to extract and organize each investigator's organizational affiliation history.

4.4.3.1 Scraping LinkedIn using Python

To automatically extract and organize information on each investigator's organizational affiliation history, I use the Python programming language and commands from the BeautifulSoup software package.²⁷ BeautifulSoup provides Python-based commands for extracting data from HTML and XML web pages, a process known as "web-scraping." Since web pages from the online professional networking service LinkedIn serve as the key data sources for many of the investigators' professional backgrounds, I design and implement a Python script using BeautifulSoup commands to web-scrape LinkedIn web

²⁷ More information about the BeautifulSoup software package can be found at the package's documentation website: <https://www.crummy.com/software/BeautifulSoup/bs4/doc/>

pages. The script finds certain HTML tags that the LinkedIn websites use to encode information about a LinkedIn user's professional history and collects the organization name and dates associated with the tags. In a normal web browser, the information associated with the tags appears as each organization at which a LinkedIn user worked or studied and over what specific years and months the user worked or studied at that organization. The script uses the collected information to prepare a file that contains the name of each investigator, each year of interest in my data set, and the name of each organization at which the investigator worked or studied during that year.²⁸ I apply standard data-cleaning procedures to the file, e.g. removing useless affiliations such as "Eagle Scout Troop" and developing standard names for common affiliations like "General Electric."

4.4.3.2 Codings

To the organizational affiliations data gathered through web-scraping principal investigator's LinkedIn pages and other background sources, I then apply several codings related to key factors thought to influence patent production. I research each affiliation individually and determine, for example, whether the affiliation is domestic (based in US) or foreign; whether the affiliation is a government, private industrial, academic, or non-profit organization; and whether the affiliation is in one of many sectors relevant to lighting. A list below describes the code-variables and how I determined the value of each code-variable. I then cross-reference between my affiliation-codings and each inventor's history of affiliations, applying the appropriate codings to each inventor-year. For example,

²⁸ As mentioned above, investigators whose professional background sources (whether LinkedIn web pages or some other source) lacked an annual level of detail as to where the inventor worked or studied were dropped from my sample of investigators.

if an investigator was at a university for part of one year and a non-US-based firm for another part of the same year, I apply codings to indicate that the investigator-year involved affiliations with both an academic organization and a foreign firm. This example is not exhaustive, and I apply many more codings to each investigator-year. In addition to coding each affiliation, I also create new variables to track the investigator's time at each affiliation and whether the inventor changed affiliations in a given year.

The list of code-variables applied to each affiliation, how the value of each variable is determined, and an example of each variable is as follows:

- “PI_Status” – set to 1 for any year after which a given investigator became funded by the DOE SSL program. This coding used data acquired from the DOE SSL program itself on when each investigator became funded.
- “CL_Provision” – set to 1 for 2006 and every year after. The DOE SSL program's compulsory licensing provision came into existence in response to the EPLA of 2005, and as such all PIs became subject to the provision by 2006. The compulsory licensing provision affects retroactively the PIs who became funded by the program prior to 2006.
- “ACADEMIC” – set to 1 for an organization that is a university, college, or other academic institution; set to 0 otherwise. For example, I code California Institute of Technology as 1 and General Electric as 0.
- “LARGE_FIRM” – set to 1 for an organization that is a private industrial firm having existed for more than two decades or self-identifying as having operations in multiple

technology sectors; set to 0 otherwise. For example, I code General Electric as 1 and Soraa, Inc. – a small SSL start-up – as 0.

- “SMALL_FIRM” – set to 1 for an organization that is a private industrial firm having existed for fewer than two decades or self-identifying as having specialization in only one technology sector. For example, I code Soraa, Inc. as 1 and General Electric as 0.
- “GOVERNMENT” – set to 1 for an organization affiliated with the national government or a local government of any nation, 0 otherwise. For example, I code Sandia National Laboratories as 1 and General Electric as 0.
- “NON-PROFIT_INSTITUTE” – set to 1 for an organization that represents the interests of multiple private firms or is responsible for lobbying on behalf of other organizations. Few organizations fall into this category. For example, I code the American Institute of Aeronautics and Astronautics as 1 and General Electric as 0.
- “USA” – set to 1 for any organization self-identifying as headquartered in the United States, 0 otherwise. For example, I code General Electric as 1 and Nippon Telephone and Telegraph as 0.
- “California” – set to 1 for any organization self-identifying as headquartered in the state of California, 0 otherwise. For example, I code UC Berkeley as 1 and Princeton University as 0.
- “NE” – set to 1 for any organization headquartered in the Northeastern United States, which includes only the following states: Massachusetts, Connecticut, Rhode Island, New Hampshire, Vermont, and Maine. Set to 0 otherwise. Organizations headquartered in New

York are set to 0. For example, I code Massachusetts Institute of Technology as 1 and University at Buffalo as 0

- “EU” – set to 1 for any organization headquartered in the continent of Europe, and set to 0 otherwise. For example, I code Bayer Material Science as 1 and General Electric as 0.
- “Japan” – set to 1 for any organization headquartered in the nation of Japan, and set to 0 otherwise. For example, I code Nippon Telephone and Telegraph as 1 and General Electric as 0.
- “EastAsiaOther” – set to 1 for any organization headquartered in an East-asian nation other than Japan, and set to 0 otherwise. Organizations headquartered in China, South Korea, and Taiwan are set to 1. For example, I code Peking University as 1 and Nippon Telephone and Telegraph as 0.
- “Lighting” – set to 1 for any organization who self-identifies as having operations in the manufacture or sale of lighting technologies and who has a relationship to SSL through producing or selling SSL devices (e.g. bulbs, luminaires, etc.), and set to 0 otherwise. For example, I code the lighting manufacturer General Electric as 1 and materials research firm Applied Materials as 0.
- “Materials” – set to 1 for any organization who self-identifies as having operations in materials science and technologies and who has a relationship to SSL through researching materials for lighting applications, and set to 0 otherwise. This does not include organizations involved in the production or sale of complete LED devices. For example, I

code the major chemical firm Eastman Kodak as 1 and lighting manufacturer General Electric as 0.

- “LED” – set to 1 for any organization who self-identifies as having operations in producing completed *inorganic* LED devices, and set to 0 otherwise. Most of the organizations that I code as 1 for the “Lighting” variable are also coded as 1 for the “LED” variable, because only inorganic LED technologies have reached production as lighting devices. Conversely, organic LED (“OLED”) technologies haven’t yet been turned into devices for manufacture and sale. For example, I code General Electric as 1 and OLEDworks as 0.
- “OLED” – set to 1 for any organization who self-identifies as having operations in research supporting *organic* LED technologies, and 0 otherwise. In contrast to the “LED” variable’s overlap with the “Lighting” variable, most organizations coded 1 for the “OLED” variable are also coded 1 for the “Materials” variable. For example, I code OLEDWorks as 1 and CREE as 0.
- “Electronics” – set to 1 for any organization who self-identifies as having operations in electronics, including the assembly of non-lighting devices and research into non-lighting electronics technologies. Set to 0 otherwise. For example, I code Hewlett-Packard as 1 and Eastman Kodak as 0.

In addition to the variable codings above, I also added to the dataset several calculated variables. The calculated variables use functions acting on the other variables or codings in the dataset. The calculated variables are as follows:

- “SubjectToCL” – calculated as 1 for all investigator-years having a 1 for PI_Status and a 1 for CL_Provision, in essence forming a single coding to identify which investigator-years were subject to the DOE SSL program’s compulsory licensing provision. I added this indicator to simplify interpretation and because tests showed improved regression model fits when the CL_Provision variable was removed.
- “YearsSinceEarliestData” – calculated as the number of years since the investigator’s first year of available affiliation data. I added this variable to approximate age differences between investigators, under the assumption that investigators whose affiliation data stretches back further in history are older than investigators with shorter affiliation histories.
- “YearsSinceFirstAcademic” – calculated as the number of years since the investigator’s earliest academic affiliation. I also added this variable to approximate age differences.
- “AffilChange” – calculated as 1 for a year in which an investigator’s affiliations changed, and 0 otherwise. I added this variable in an attempt to identify whether job changes were affecting investigators’ patent production, hypothesizing that the time-consumption of job changes or willingness to leave a current job would reduce an investigator’s patent production.
- “CUM_ACADEMIC,” “CUM_LARGE_FIRM,” etc. – for each coding, I calculated the cumulative number of years that an investigator has had an affiliation with that coding. For a given year, these cumulative-codings represent the investigator’s total experience with an affiliation of the given coding. I hypothesized that more cumulative experience in an

affiliation of a given coding would multiply whatever effects an affiliation of a given coding would have on patent production.

4.4.4 Advantages of chosen data-collection methodology versus alternatives

The approach used in this study has many advantages and superior qualities to alternative approaches. Foremost, web-scraping the LinkedIn profiles and using other professional background sources dominates the use of a survey of the funded principal investigators on pure grounds of response rate. Since the current study was not conducted in association with the DOE SSL program, the study has no power to compel high response rates among the investigators to a professional background survey. The same condition prevents any sort of mass request for the investigators' resumes or CVs from having much more success than a survey. Having no rapport, let alone a mere professional connection, with any of the investigators strongly diminishes the likelihood that any would respond to inquiries or requests for resumes and CVs. Interviewing each participant for his or her professional background is out of the question on the grounds of financial costs and time-consumption alone. Even interviewing the same number of investigators as for which I was able to get good background information through web-scraped pages and online sources would present prohibitive costs and a far less efficient use of resources. As to the accuracy of information obtained through online sources, the transparency of public web pages and CVs versus privately shared resumes and CVs arguably provides greater incentives for those presenting their backgrounds through public web pages and CVs to present truthfully. As demonstrated by the famous case of RadioShack CEO Dave Edmonson's falsified

resume,²⁹ good reason exists to believe that resumes and CVs don't always provide more accurate information than public sources.

To those who might try to convince themselves that the use of LinkedIn profiles and online sources on professional backgrounds creates a selective effect similar to that of analyzing funded principal investigators – this is a foolhardy proposition. The proposition rests on an assumed causal mechanism between curating an online professional background source – e.g. a LinkedIn profile or online resume – and patenting. *Prima facie*, no such mechanism exists. The USPTO's process for granting patents takes no account of the applicant's "online presence," of whether the applicant has a LinkedIn profile or posted a CV to the web, or the applicant's knowledge and ability to take such actions. Since there is clearly no causal mechanism, the doubter is reduced to offering conflating correlations – for example, that of persons working at a small firm. The small firm may have an intellectual-property-focused strategy and thus drive their employees toward patenting, and the small firm may also drive employees to curate professional "online presence" in order to attract seed funding. Thus, the worker's online presence does not cause patenting, but the worker is more likely to both patent and have an online presence (and thus be present in the sample of investigators) because he or she works at a small firm. As will be shown, small firms do not dominate the sample of principal investigators, and my coding scheme represents small firms and therefore allows the data to account for any effect of working at a small firm both on patenting and on being in the sample of investigators. Moreover, the critical reader can

²⁹ Morrison, M. "RadioShack's Lesson: Trust, but verify" *Bloomberg*, Feb. 22, 2006. Available at <https://www.bloomberg.com/news/articles/2006-02-21/radioshacks-lesson-trust-but-verify>
Norris, F. "RadioShack Chief Resigns After Lying." *The New York Times*, Feb. 21, 2006. Available at <https://www.nytimes.com/2006/02/21/business/radioshack-chief-resigns-after-lying.html>

clearly see that such a proffered story for correlational conflation stretches the limits of believability to the breaking point.

As for the patent data collected, the Fung Institute's disambiguated patent database represents the superior choice. Certainly, having a prepared database of patent record information reduces costs relative to web-scraping the USPTO's online records, the most accessible of which allow querying of only one full record at a time.³⁰ Beyond the advantages of having a database already prepared, the Fung Institute database overcomes the most crucial challenge for any study using inventors as a unit of analysis – that of disambiguating patent records by inventor. Indeed, the disambiguation by inventor represents a key and fundamental contribution of the Fung Institute database to research using patents, and the contribution enables a host of future inventor-centered research to come. Disambiguating any existing database of un-disambiguated patent record information would present a far costlier alternative and simply doesn't make sense. Moreover, whatever the merits and demerits the Fung Institute's database are, they are well known because the database is public. Acquiring a database that must be licensed presents greater epistemic risks at the study's outset because the merits and demerits of the database are not known. Moreover, by the time the merits and demerits are known, the licensing costs are sunk and irreversible – not to mention that the licensing costs can be completely avoided by using the Fung Institute database, another advantage.

4.4.5 Results of data filtering: Reducing patents to only those made by authors with professional background information available online

³⁰ <http://patft.uspto.gov/>

The data collection procedure used here leaves intact a significant number and share of the set of patents and investigator-years that make up the dependent variables. As shown in Table 8 below, the large majority of funded principal investigators have adequate professional background information to make them worthy of inclusion in the study. Similarly, Table 8 also shows that the large majority of patents were made by funded principal investigators with adequate professional background information. Table 8 also shows that the majority of patents granted to investigators after they became funded by the DOE SSL program belong to investigators with adequate professional background information. All of this information gives ample reason to believe that the data collection procedure for this study clearly outperforms some of the alternative procedures discussed above, such as a simple survey. Moreover, Table 8 also shows that the data collection procedure leaves a healthy-sized sample dataset with a large N intact and ready for analysis.

Table 8: Counts and proportions of patents, investigators, and patents granted to investigators post-funding produced by the study’s data collection procedure.

| | |
|--|---|
| Patents (1996 to 2014) | |
| 3260 | Number of total patents in the dataset |
| 1145 | Number of total patents made by an inventor with adequate professional background data |
| 35% | percentage of patents from CL investigators with adequate professional background data |
| Patents granted to funded principal investigators | |
| 1789 | total patents from post-funding investigators, all |
| 534 | total patents from post-funding investigators with adequate professional background data |
| 30% | percent of patents from post-funding investigators with adequate professional background data |
| Principal investigators | |
| 146 | Total investigators (through 2014 of DOE SSL program) |
| 71 | Total investigators with adequate professional background data (i.e. the sample investigators) |
| 49% | Percent of total investigators with adequate professional background data |
| Sample dataset size | |
| 20 | Years of data used for each investigator |
| 1420 | Total investigator-year observations (N) for Pis whose bios contain adequate professional background data |

Similarly, the data collection procedure also leaves intact a balanced selection of patents produced before and after each principal investigator became funded by the DOE SSL program. If only a small portion of the patents in the study’s dataset were to have been granted after the principal investigators became funded, for example, the skewed distribution would make it challenging to identify factors that increased patenting among funded investigators. Moreover, we would have great opportunity to conclude that DOE SSL program’s patent licensing policy did reduce patenting among funded principal investigators on the grounds of such skewed data alone. Fortunately, as Table 9 shows, the sample dataset retains a balance of patents that were made before an investigator became funded and after an investigator became funded. Table 9 shows that the patents in the

sample dataset represent inventions by principal investigators prior to funding and after funding in roughly even measure. Importantly, Table 9 also shows that the evenness of representation applies to inventors with adequate professional background information, so that the final sample data set retains good representation of pre-funding patents and post-funding patents.

- Before PI status
- After CL provision (i.e. after 2005)
- Before CL provision
- Under treatment (i.e. after CL provision AND after PI status)
- Under control (i.e. before CL provision OR before PI status)

Table 9: Counts and proportions of patents granted before and after funding of each principal investigator

| Patents granted after funding | |
|---|--|
| 1789 | total post-funding patents |
| 534 | total post-funding with CL patents from investigators with professional background data |
| 30% | percent of patents from post-funding with CL investigators with professional background data |
| Patents granted prior to funding | |
| 860 | total pre-funding patents |
| 611 | total pre-funding with CL patents from investigators with data |
| 71% | Percent of patents from pre-funding with CL investigators with data |

4.5 Data analysis and findings

4.5.1 Aggregations of patent data

First, I show the gross result of differences in patent count between funded investigators and non-funded investigators. Teece's Appropriability Regimes hypothesis leads us to expect that post-funding investigators would produce fewer patents than pre-funding investigators because of the DOE SSL program's policy towards patent licensing. Table 10 shows the total patents granted to pre-funding investigators and the total patents granted to post-funding investigators. The total produced by sample investigators before they were funded by the DOE SSL program slightly exceeds the total produced by the same investigators after they were funded.

Table 10: Total patents produced by sample investigators and percentages of total patents with breakouts by funding status

| | total patents | percent of total |
|---|---------------|------------------|
| from sample investigators between 1993 and 2014 | 1145 | 100% |
| ...before funding by DOE SSL program | 611 | 53% |
| ...after funding by DOE SSL program | 534 | 47% |

Examination of the patents from principal investigators per year of the analysis period shows some expected trends. First, as shown in Figure 9, patents from investigators not yet funded by the DOE SSL program rise over time prior to the program's inception – from 1996 to 2005, representing growing interest in SSL intellectual property commensurate with the development of white-light LEDs. Investigators who would later be funded by the DOE SSL program were, before 2005, actively pursuing patents. Second, as more and more of the investigators become funded by the DOE SSL program from 2005 to 2014, more of the patents produced come from funded investigators and fewer patents come from non-funded investigators. Later in the study period, there are simply fewer and fewer non-funded investigators to produce patents.

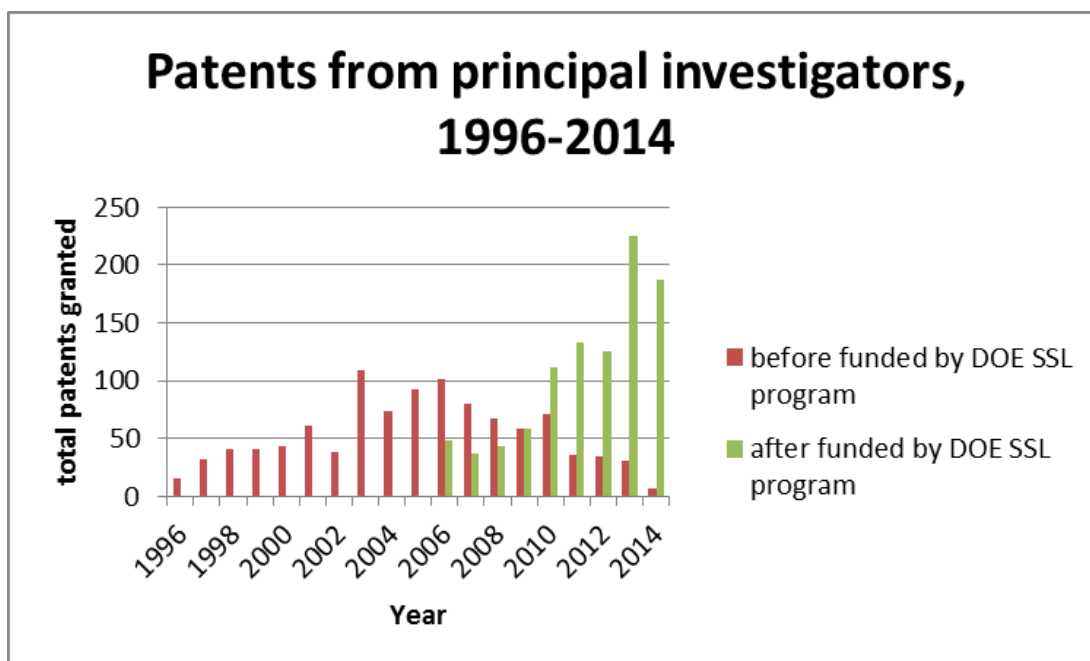


Figure 9: Total patents granted to investigators before and after being funded by the DOE SSL program

To provide further context on the composition of the investigators, Figure 10 displays the investigator-affiliations with breakouts by four main categories: Academic, Large firm, Small firm, and Government. Over time, the investigators move from a majority of Academic affiliations in 1996 to a plurality of Small firm affiliations in 2014. Figure 10 shows that, after the inception of the DOE SSL program in 2005, the majority of the investigators during the study period have either a Small firm affiliation or a Large firm affiliation.

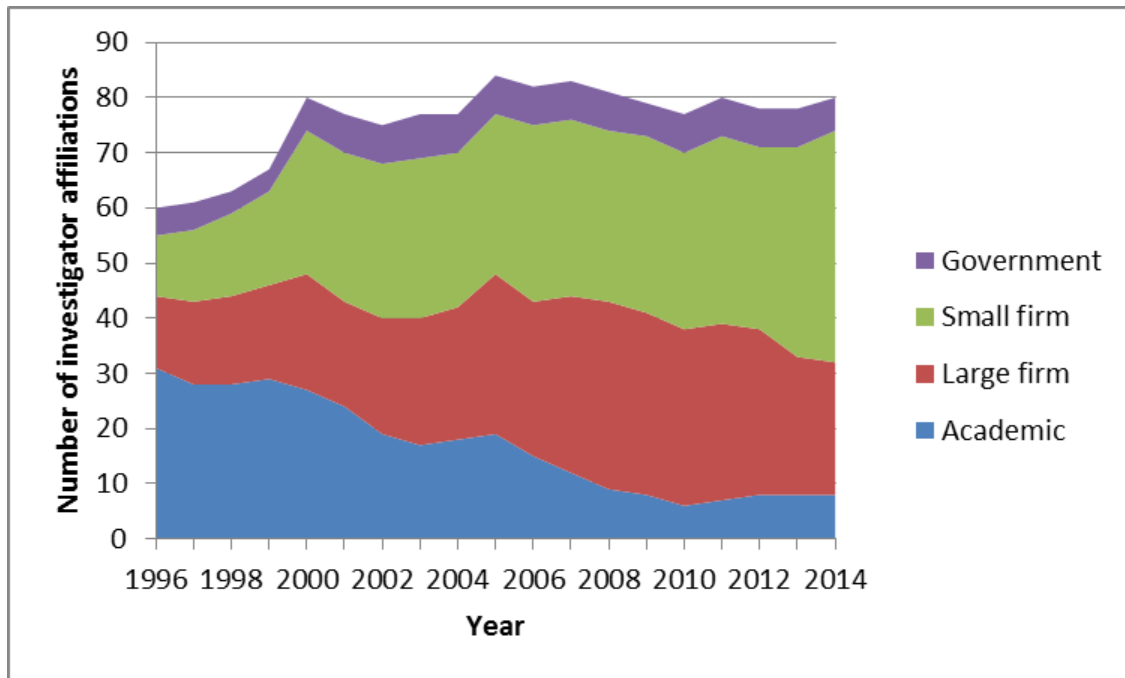


Figure 10: Investigator affiliations during the analysis period. The results sometime exceed the number of sample investigators because, in a given year, each investigator may have more than one affiliation.

Similarly, Figure 11 displays the number of investigator affiliations with breakouts by four main geopolitical categories: “US,” “EU,” “Japan,” and “East Asia – Other.” The “East Asia – Other” category represents affiliations with organizations located in South Korea, China, and Taiwan. Figure 11’s results show that the wide majority of investigators have affiliations with US-based organizations.

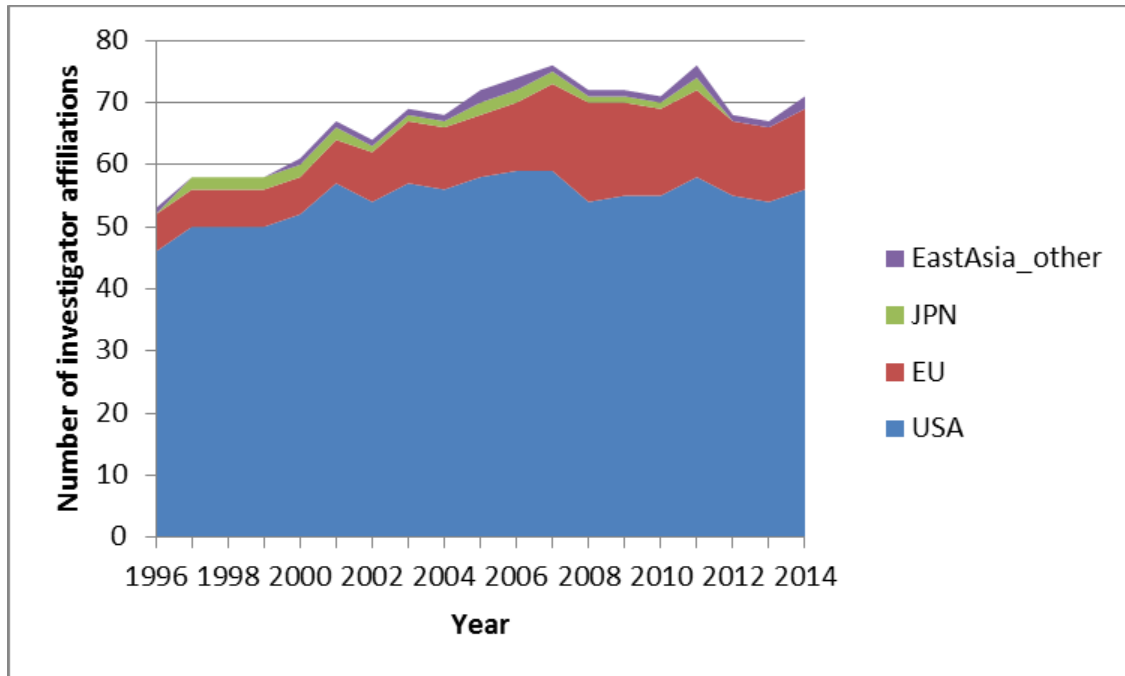


Figure 11: Investigator affiliations during the analysis period. “USA” represents affiliations with US-based organizations; “EU” for the European Union; “JPN” for Japan; and “EastAsia_other” for China, South Korea, and Taiwan³¹

The sample of investigators grows with time, as shown in Figure 12. Observed increases in patenting by post-funding investigators might represent an increase in the total number of investigators in the sample. In other words, because the actual sample of investigators is growing with time, we may have a greater number of patents post-funding while the patents-per-investigator for post-funding investigators remains lower than that for pre-funding investigators.

³¹ The results sometime exceed the number of sample investigators because, in a given year, each investigator may have more than one affiliation.

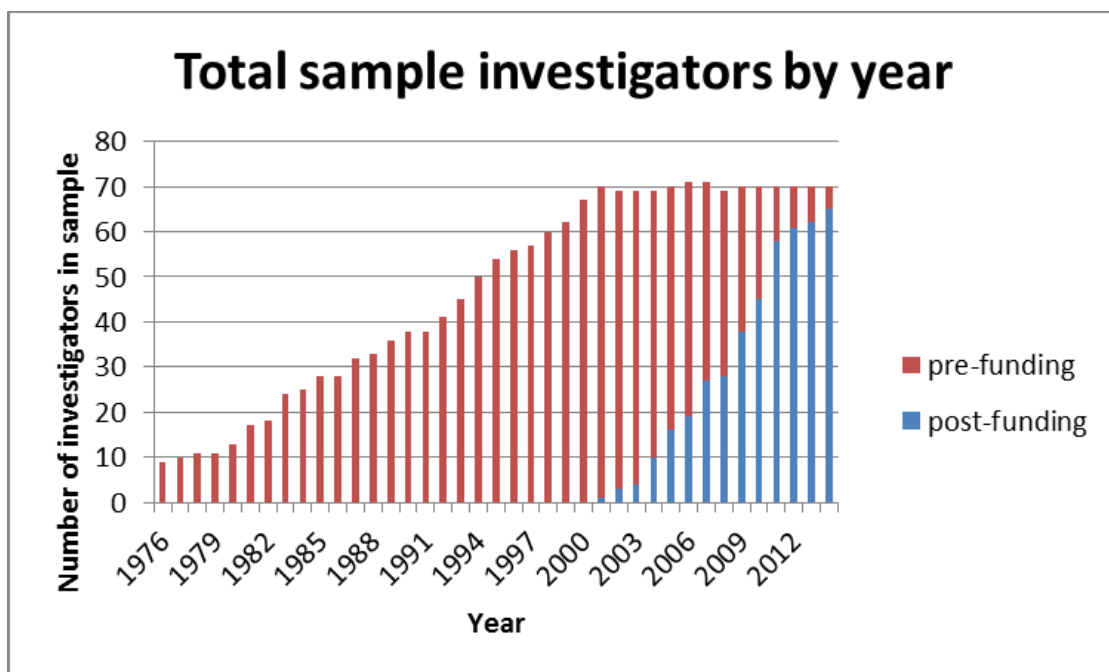


Figure 12: Time series of total sample investigators per year. An investigator “enters the sample” in the earliest year for which adequate background information on the investigator is available.³²

To examine patent production without interference from the total number of sample investigators, I compare patents-per-investigator over time between the pre-funding and post-funding categories and examine total investigators over time. Figure 13 shows average patents-per-investigator over time, with breakouts for before-funding and after-funding. Figure 13’s results indicate that (1) average patenting per investigator generally increased over the study period, and (2) average patenting by funded investigators largely kept pace with average patenting of non-funded investigators after the DOE SSL program’s licensing policy was introduced in 2005. However, Figure 13 shows that for many years after the

³² The “pre-funding” bars for each year represent the number of sample investigators who had yet to be funded by the DOE SSL program, while the “post-funding” bars represent the number who had become funded by the program.

licensing policy's introduction, patenting by non-funded investigators exceeds patenting by funded investigators.

Figure 13 shows that, for most years of analysis, the investigators subjected to the licensing policy were granted fewer patents than investigators not yet subjected to the licensing policy. However, the differences between the two groups are not very large, especially relative to year-to-year variation in average patents per investigator for both groups and across all investigators. The results of Figure 13 challenge the hypothesis that the program's licensing policy discouraged patenting.

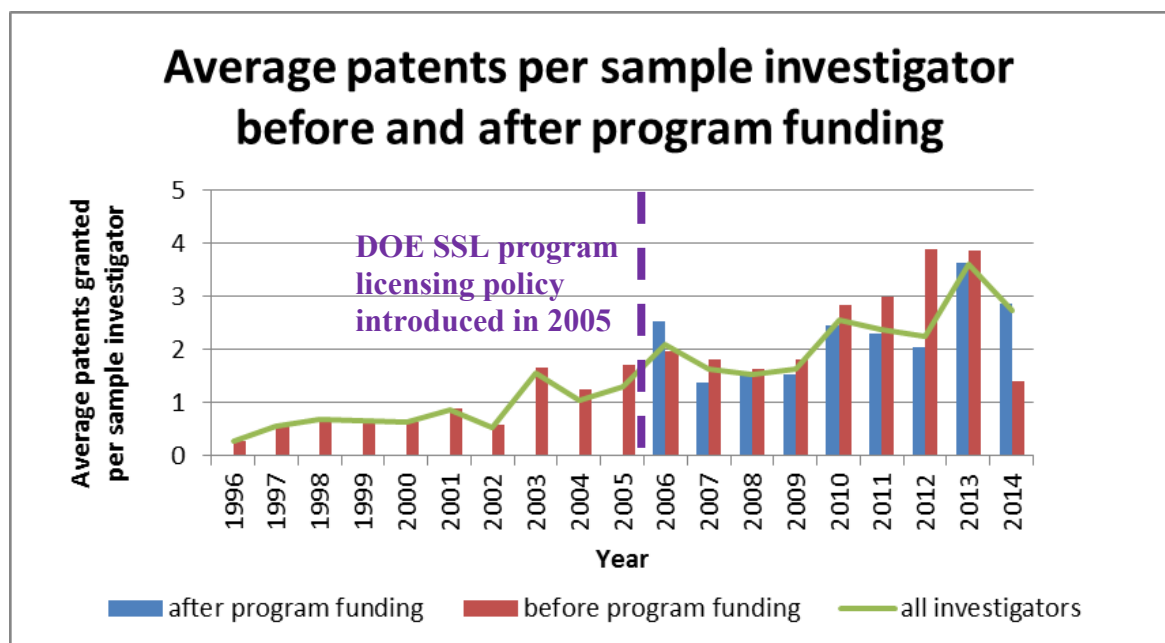


Figure 13: Time series of patents per investigator, with breakouts by whether the patents came from a funded investigator (i.e. after program funding) or an investigator who had yet to be funded (i.e. before program funding)

Next, we pursue a modified version of the hypothesis. Since certain firms (usually small firms) have strategies that depend more heavily upon intellectual property than other firms (usually large firms), I hypothesize that the licensing policy may have had a discouraging effect among small firms but not among large firms.

To test the hypothesis on firm size, I calculate an average patents-per-inventor categorized by the size of the firm with which the investigator affiliates. The calculation necessarily only includes patents from investigators affiliated with firms, as opposed to e.g. investigators affiliated with government institutions. Figure 14 below shows that, contrary to the idea that small firms more frequently have an intellectual-property-driven strategy and therefore patent more than large firms, small firm sample investigators generally patented on average as much or less than large firm sample investigators. Rarely do sample investigators affiliated with small firms patent more on average than sample investigators affiliated with large firms.

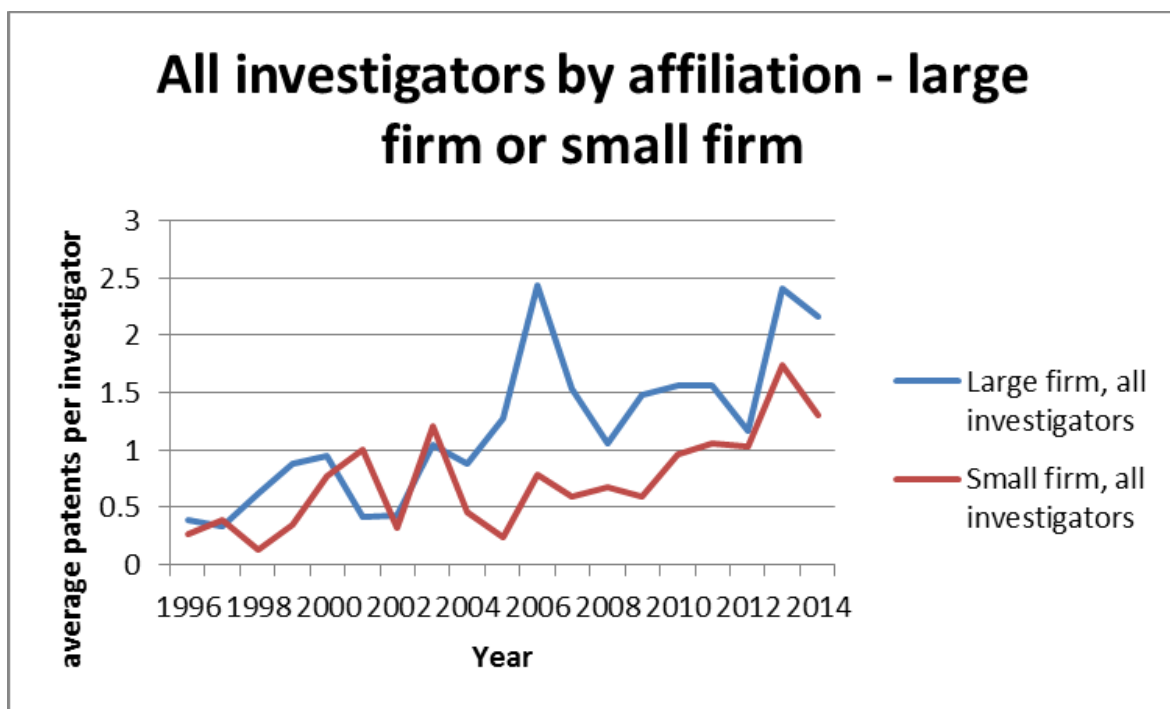


Figure 14: Average patents-per-investigator categorized by small-firm investigators and large-firm investigators.

Despite the contrary finding on average patenting per investigator between large and small firms, the modified hypothesis holds that a negative effect on average patenting per investigator could still be larger for small firm investigators than for large firm investigators. Figure 15 and Figure 16 show the average patenting per investigator during the analysis period for small firm investigators and for large firm investigators, respectively. While funded investigators for both large and small firms experience a large increase in patents-per-investigator during 2006, the funded investigators generally patent slightly less than the yet-to-be-funded investigators for all years except 2013 and 2014 – for both categories of firms. Figure 15 does not show greater differences between before-funding and after-funding investigators affiliated with small firms than the differences shown in Figure 16 for investigators affiliated with large firms.

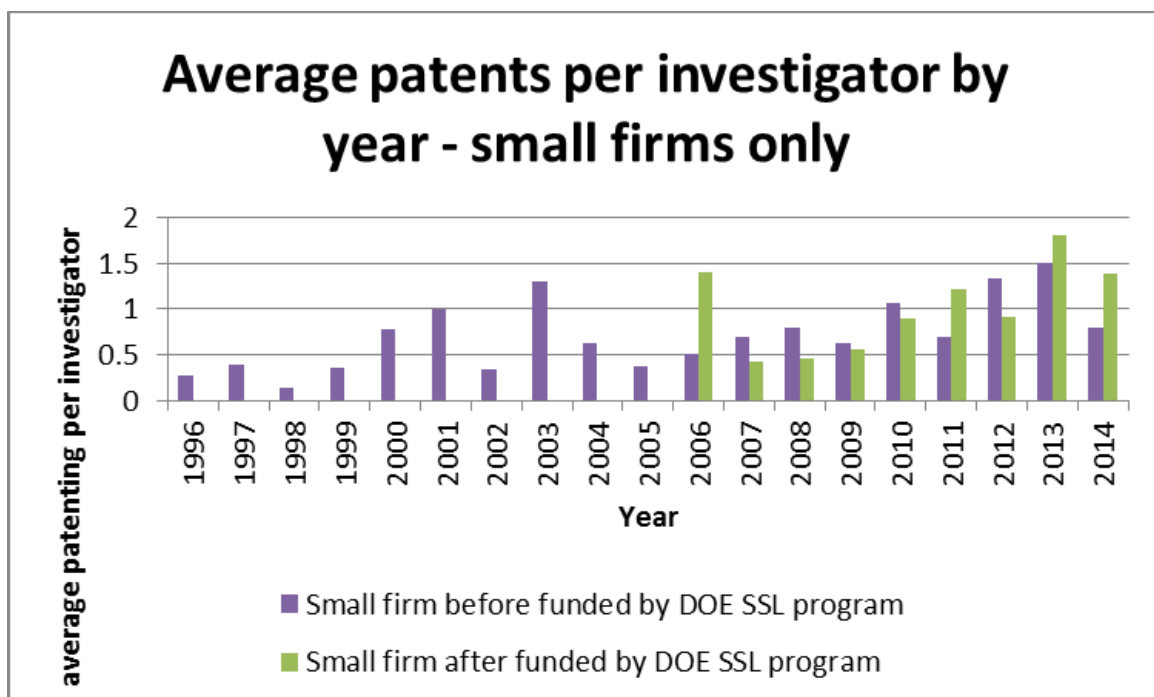


Figure 15: Average patents per investigator for small firms

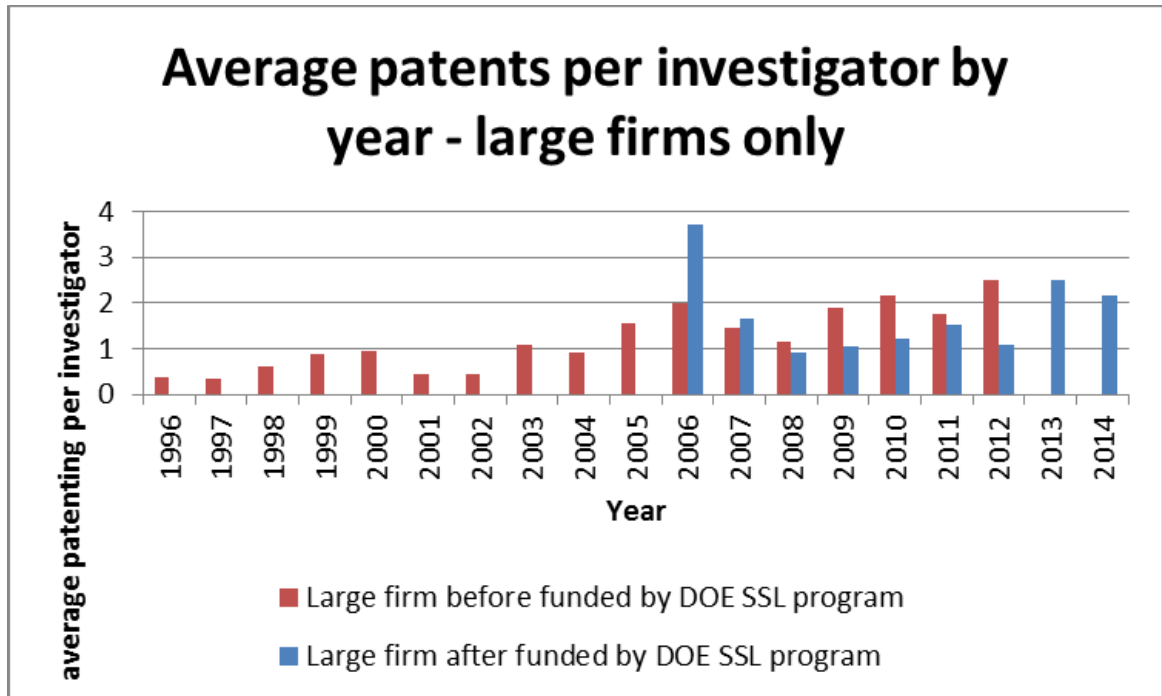


Figure 16: Average patents per investigator for large firms

Table 11 provides the average patents-per-investigator for investigators affiliated with large firms and small firms, before and after funding by the DOE SSL program. For both large-firm-affiliated and small-firm-affiliated investigators, the average patents per investigator of post-funding investigators exceeds that of pre-funding investigators.

Table 11: Average patenting per investigator, 1996 to 2014, categorized by funding status and firm size

| | large firm | small firm |
|----------------|------------|------------|
| before funding | 1.111498 | 0.697248 |
| after funding | 1.569061 | 1.014851 |

To begin inference as to the probability distribution appropriate for parametric analysis of patent production by sample investigators, I prepare some histograms showing the

distribution of patent production across all sample investigator-years. Figure 17 and Figure 18 show the total distribution of all values of patent production (e.g. 0 patents granted, 1 patent granted, 2 patents granted, etc.) for all investigator-years with breakout by pre-funding and post-funding. Figure 18 focuses on a subset of patent production values to allow the viewer to observe with clarity the distribution of less-frequently-occurring values of patent production, which are values in the upper ranges. The distributions show several features of the data that contradict assumption of common regression analysis but that also may be easily expected from understanding the US patent process:

- No investigator produced a negative number of patents in any investigator-year
- The most common number of patents produced by a given investigator in a given year is zero, and the second-most-common number is one
- The distribution falls dramatically as the number of patents produced increases; only very rarely do investigators in a given year produce a number of patents as high as, say, 10 or 15.
- Without checking for correlation with a normal distribution, we can see clearly that the patent production data are not normally distributed
- The data do not remotely appear to match a normal distribution

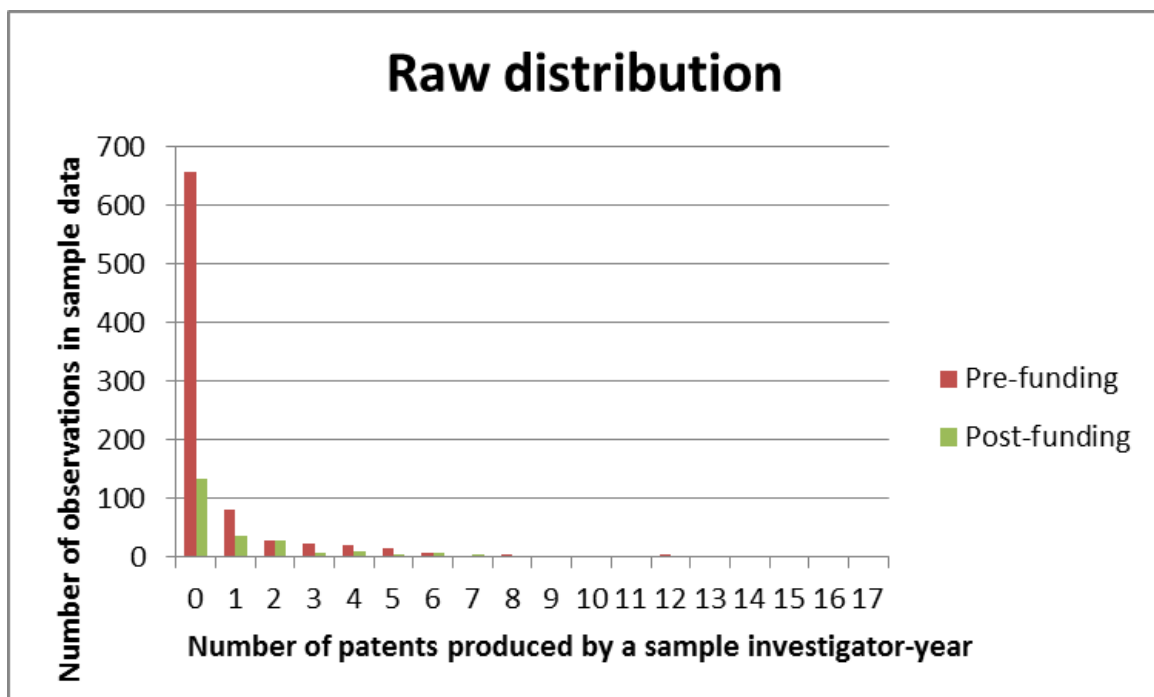


Figure 17: Raw distribution of observed values for patents produced by a given investigator-year across all sample data, categorized by investigator funding status.

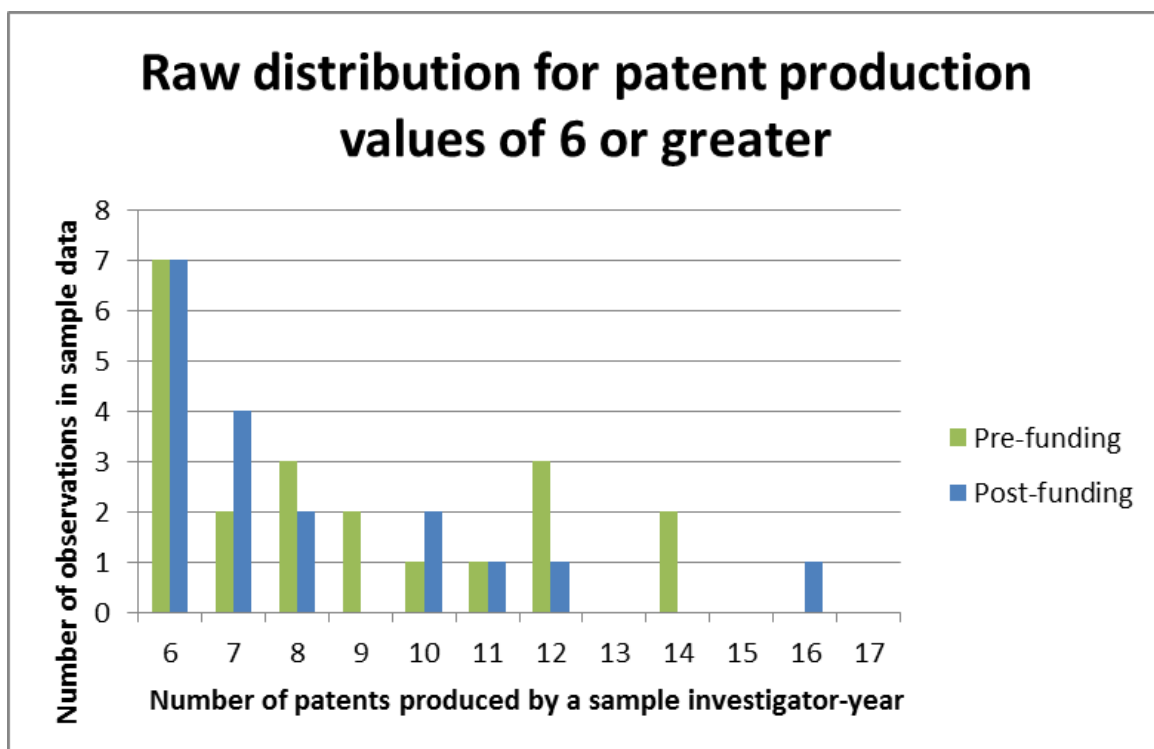


Figure 18: Data from Figure 17, restricted only to patent production values of 6 or greater (provided for clarity into distribution of less-frequently-observed patent production values).

Contrary to matching a probability density function (PDF) described by the normal distribution, the patents-per-investigator-year data appear to more closely match the PDF of an exponential distribution with a relatively low lambda value. Figure 19 shows the patent data aggregated across both pre-funding and post-funding investigators overlaid by an exponential distribution PDF having a lambda value of 1.8 and a scalar value of 2700.³³ Instead of a normal distribution PDF, the patent data appear to much more closely match the exponential distribution PDF.

³³ The lambda value of 1.8 and the scalar value of 2700 were determined via trial-and-error to offer an adequate combination of parameters for modeling the patent data distribution.

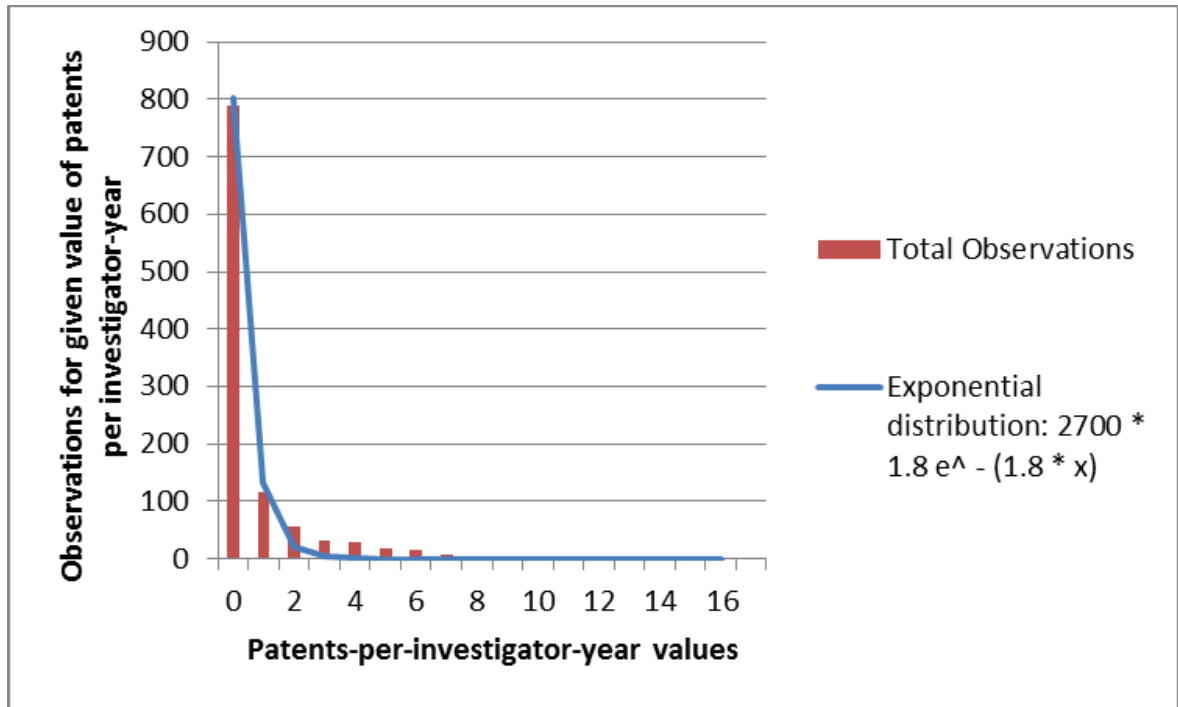


Figure 19: Distribution of observations across values of patents-per-investigator-year, with fitted exponential distribution superimposed

A typical exponential probability density function takes the form

$$\Pr(xx) = ss * \lambda * ee^{-\lambda * xx}$$

Where s represents a scalar value and λ represents the distribution's defining parameter.

As shown in Figure 19, the value $s = 2700$ and $\lambda = 1.8$ provide adequate fit for the observations of patents-per-investigator.

4.5.2 Regression models fitted to patent data

In further effort to detect and observe any clear negative effect on patent production from the DOE SSL program's policy, I construct from the data a model via ordinary least squares regression. To construct the model, I use the open-source software package R. I interpret

the model's coefficients and related statistics for insights into the effects on investigator patenting behavior of the DOE SSL program's compulsory licensing policy.

I chose to form a linear model from the predictors collected, coded, and calculated in the dataset, particularly with interest in interaction terms between other predictors and the compulsory licensing indicators. I chose to use linear combinations of the variables (i.e. a "linear model") on grounds of adequacy and that more complex combinations (e.g. non-linear models) brought further modeling and computational complexities without proportionate benefits and therefore lacked reasonable justification. My interest in the interaction effects (i.e. secondary effect) between certain predictors and the compulsory licensing indicators stemmed from intent to verify whether a marginal effect of the compulsory licensing provision on patent productivity occurred only under certain conditions. Including interaction terms among the model's predictors might reveal whether the compulsory licensing provision affected only investigators affiliated with small firms, for example. The use of interaction terms to identify such circumstantial marginal effects is generally referred to as a "difference-in-differences" approach.

4.5.2.1 Model selection via stepwise regression

To find a regression model of superior fit and predictive capability, I use stepwise regression model selection. One can build a number of models approaching infinity from a given dataset, but only models with superior predictive capability offer meaningful insights into the dataset's patterns.³⁴ As such, sticking to models of better fit is especially

³⁴ A regression model may have several "statistically significant" coefficients, but if the model has low fit and predictive capability relative to other models one can build from the same data, the model offers little

important for decision-making, policy-making, and hypothesis testing. Automated processes have long existed for identifying from a given dataset's portfolio of all possible regression the models of superior fit, and AIC-based Stepwise Regression has long been a standard and more-than-adequate approach for identifying models of best fit. AIC-based Stepwise Regression proceeds in an iterative fashion by forming a regression model, then adding or removing a variable from the current model to form a new model, and then computing and comparing the two models' AIC³⁵ statistics. If the AIC statistic has decreased, the new model's fit is substantially better than the old model's fit. The process then starts over using the new model as the base of comparison; the process continues iterating until the AIC statistic stops decreasing, at which point the process has identified a best-fitting model.

Because a high number of interaction terms create computational challenges for AIC-based Stepwise Regression and fitting regression models in general, I restricted the number of interaction terms allowed in the AIC-based Stepwise Regression process. I started the AIC-based Stepwise Regression process using a small model with only three variables and two interaction terms,³⁶ and allowed the process to add or remove single variables until reaching an optimum AIC. I did not allow the process to add or remove any interaction terms, however, and instead performed manual stepwise regression with interaction terms.

insight into the dataset's actual patterns. Moreover, it is misleading to present interpretations of a poor-fitting model when one can easily construct and interpret a better-fitting model.

³⁵ AIC stands for Akaike Information Criterion and is an estimate of the information lost by a given regression model relative to a hypothetical best model. As such, when the AIC statistic is minimized, statisticians consider information loss to have been minimized and a best-fitting model to have been found. While other statistics and estimators have been applied to the same problem (e.g. BIC, the Bayesian Information Criterion), AIC is of standard use and for my dataset presents no challenges or disadvantages.

³⁶ The variables were LARGE_FIRM, SMALL_FIRM, and SubjectToCL; the interaction terms were LARGE_FIRM*SubjectToCL and SMALL_FIRM*SubjectToCL

After I used stepwise regression to identify a model of good fit, I further used manual experimentation with adding and subtracting certain interaction terms in order to identify a model of better fit. Such manual adding of interaction terms produced models of substantially better goodness-of-fit, as measured by the adjusted R-squared statistic. Through such experimentation, I identified a model of superior fit that also had reasonable interpretative value, and I report that model in the results below.³⁷

4.5.2.2 Model statistics and interpretations

Table 12 shows coefficients, P-values, adjusted R-squared value, and other critical model statistics.

³⁷ Moreover, the reported model's goodness-of-fit is more than acceptable for the field of study. Scholars from prestigious institutions (Cambridge/MIT/CalTech) at leading events (the GaTech S&T Policy Conference) using regression models of patent data report adjusted r-squared statistics of similar or lower value.

We should also recognize that this is the best fit for the given dataset and that different data might produce a different model. Alternate data might come from interviews of each investigator before, during, and after their funded projects (all funded projects), which would reveal step-by-step what decisions were made to try and patent something from their research. But, such interviews are cost-prohibitive for me and tread on the income streams of various consulting firms, so what I can say – which is enough for a study – is that I looked at some relevant data, and here's what I found of relevance to the theory. So get over yourselves.

Also the reported model does not use all variables collected in the dataset. The AIC-based Stepwise Regression process revealed that many of the variables, including codings and calculations, did not add useful information when included in a regression model, so these variables were excluded from the reported model.

Table 12: Statistics for the best-fitting regression model

| | |
|--|--------------------------------|
| Dependent Variable: Patents per investigator-year | |
| Subject to Compulsory Licensing (CL) | -0.398 |
| Affiliated with Large Firm | 0.643*** |
| New-England-based Affiliation | 0.127 |
| Affiliated with Small Firm | 0.042 |
| Years since earliest data available | -0.009** |
| Materials Research Affiliation | -0.065 |
| Year | 0.056*** |
| Japan-based Affiliation | -0.817** |
| EU-based Affiliation | -0.086 |
| California-based Affiliation | -0.078 |
| Lighting Industry Affiliation | 1.859*** |
| At Large, New-England-based Firm | 0.449 |
| At Large Firm and Subject to CL | 0.036 |
| New-England-based Affiliation and Subject to CL | 3.245*** |
| Small, New-England-based firm | -0.757 |
| At Small Firm and Subject to CL | 0.142 |
| Materials-science Affiliated and Subject to CL | 0.511* |
| EU-based Affiliation and Subject to CL | 1.855*** |
| At Large, EU-based Firm | -2.145*** |
| California-based Affiliation and Subject to CL | 1.216 |
| At Small, California-based Firm | 0.726* |
| Lighting Industry Affiliation and Subject to CL | -1.906*** |
| At Large, New-England-based Firm and Subject to CL | -0.960 |
| At Small, New-England-based Firm and Subject to CL | -2.793*** |
| At Large, EU-based Firm and Subject to CL | -0.080 |
| At Small, California-based Firm and Subject to CL | -1.577* |
| Constant | -110.792*** |
| Observations | 1,242 |
| R ² | 0.188 |
| Adjusted R ² | 0.171 |
| Residual Std. Error | 1.895 (df = 1215) |
| F Statistic | 10.811*** (df = 26; 1215) |
| Note: | * p<0.1; ** p<0.05; *** p<0.01 |

Further figures help to visualize the regression model. Figure 20 compares the best-fitting regression model's confidence intervals for each of the model's coefficients.

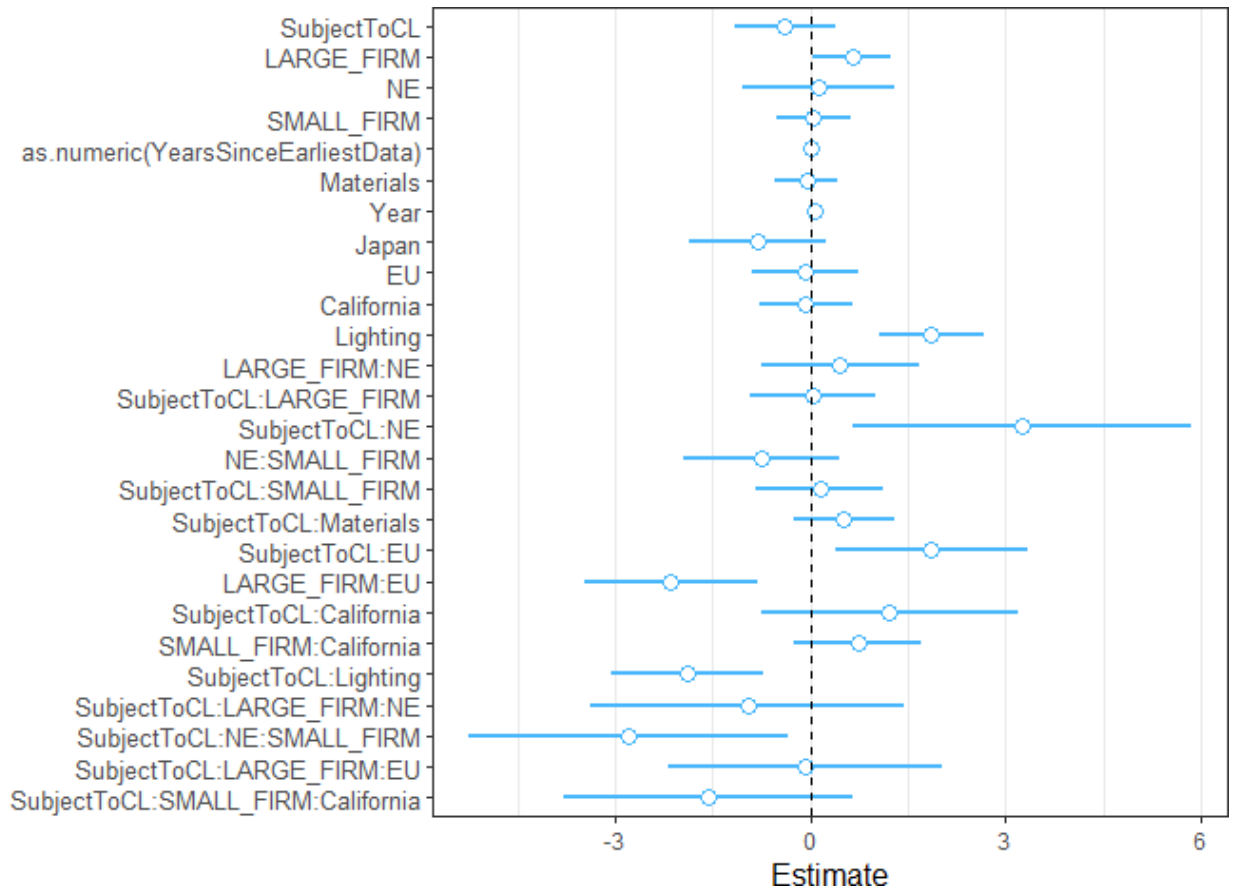


Figure 20: Coefficients and 99% confidence intervals for the best-fitting regression model

Of greatest note within the model's coefficients is that the coefficient on SubjectToCL is not statistically different from zero at the 99%, 95%, or even the 90% confidence intervals.

To provide useful interpretations of the model, the following sections provide charts displaying groups of model coefficients' confidence level. While the coefficient implies lower predicted patent production by investigators subject to the Compulsory Licensing provision in some comparisons with otherwise-similar investigators, the coefficient's

confidence intervals imply that this effect is not robust and would occur only in relatively few cases. Conversely, the model's coefficients imply much stronger effects from other variables in the dataset, including and importantly interaction terms between other variables and SubjectToCL.

Interpretation of the statistically weak coefficient on SubjectToCL offers the finding that, *in and of itself*, the DOE SSL Program's Compulsory Licensing provision had no discernible effect on investigator patent. Contrary to the hypothesis derived from Teece's Appropriability Regimes framework, the regression model evidence suggests that the forced sharing of inventions *in and of itself* did not cause the investigators to produce fewer patents.

4.5.2.3 Large firms and New-England-based organizations

The model includes interaction terms to explore what effects the DOE SSL programs' Compulsory Licensing provision had on investigators affiliated with Large Firms based in New England. Many of the NGLIA members are large firms based in the Northeastern United States (e.g. General Electric). As would-be recipients of any patent licenses forcibly shared, the New-England-based Large Firms may have given their employee-investigators subject to the Compulsory Licensing provision special direction on how to patent.

Figure 21 shows confidence intervals for the model's coefficients applied to the LARGE_FIRM, NE, and SubjectToCL variables. As shown in Figure 21, only LARGE_FIRM and the interaction term SubjectToCL:NE have 99% confidence intervals that do not include zero. The effects for both coefficients are positive. The model coefficient applied to LARGE_FIRM implies that, in 99 out of 100 comparisons with

otherwise-comparable investigators who are not affiliated with Large Firms, we can reasonably expect investigators affiliated with Large Firms to produce more patents. The model coefficient applied to SubjectToCL:NE implies that, in 99 out of 100 comparisons with otherwise comparable investigators, we can reasonably expect those subject to the Compulsory Licensing provision *and* affiliated with a New-England-based organization to produce more patents.

The other coefficients imply that, for investigators within the dataset, the following conditions have had no discernable effect on patent production:

- Being affiliated with a New-England-based organization (NE)
- Being subject to the Compulsory Licensing provision (SubjectToCL)
- Being affiliated with a Large Firm based in New England (LARGE_FIRM:NE)
- Being affiliated with a Large Firm based in New England while also being subject to the Compulsory Licensing provision.

The coefficients offer the general interpretation that being affiliated with a Large Firm or being subject to the Compulsory Licensing provision while affiliated with a New-England-based organization that is *not* a Large Firm have had positive effects on patent production. The coefficients imply no effect for Large, New-England-based Firm affiliations, whether or not the investigator is subject to the Compulsory Licensing provision. The coefficients do imply a strong positive effect for investigators affiliated with New England organizations while also subject to the Compulsory Licensing, however. Together, the set of coefficients imply that only investigators who are *not* affiliated with Large Firms while subject to the Compulsory Licensing provision and having a New England affiliation

exhibit increased patent production. In other words, investigators subject to Compulsory Licensing while at small firms or academic institutions based in New England exhibit greater patent production relative to comparable investigators at Large Firms. As such, it would appear that the Compulsory Licensing provision encouraged certain investigators to patent *more*.

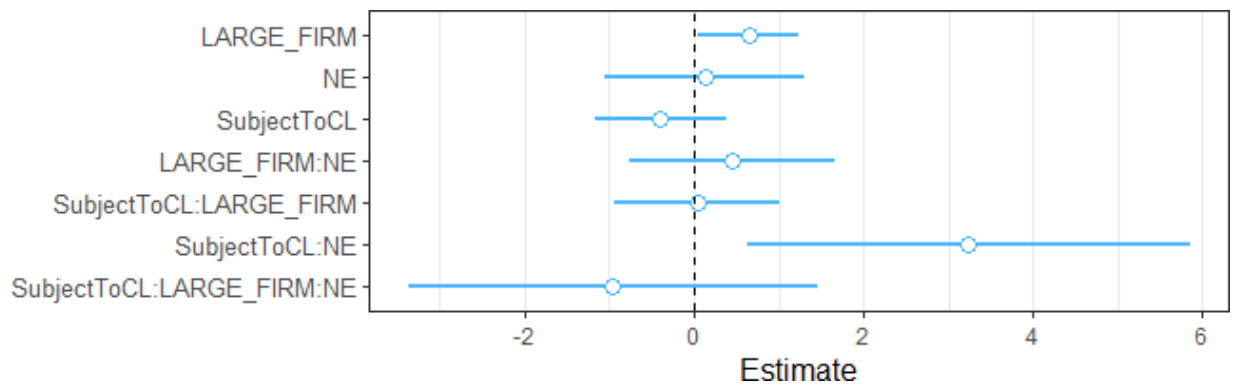


Figure 21: 99% confidence intervals for the model's coefficients applied to the LARGE_FIRM, NE, and SubjectToCL variables

4.5.2.4 Small Firms and California-based organizations

Because many US firms in SSL have grown out of the semiconductor expertise present in California's Silicon Valley and manifests particularly in small start-up firms, the model includes interaction terms to reveal the effects of Small Firm, California-based affiliations on patent production. Small Firms, particularly start-up firms in R&D-intensive industries, often pursue an intellectual-property-intensive strategy, seeking to be first-movers in acquiring a large number of patents on a specific, novel technology. These firms often hope to then make significant revenues by licensing the patents to larger firms. Forced patent sharing would clearly undermine such a strategy. As such, Small Firms based in California may have been particularly sensitive to the forced patent sharing of DOE SSL Program's

Compulsory Licensing provision and may have directed their investigators to produce fewer patents.

Figure 22 shows confidence intervals for the model's coefficients applied to the LARGE_FIRM, NE, and SubjectToCL variables. Figure 22 shows only 90% confidence intervals, as opposed to the 99% confidence intervals used in other figures, to illustrate a less likely but potentially strong negative effect of the Compulsory Licensing provision on patenting by investigators affiliated with California-based Small Firms. Particularly, the confidence interval and coefficient applied to SubjectToCL:SMALL_FIRM:California implies that, in 9 out of 10 comparisons with otherwise-comparable investigators, we can reasonably expect investigators at Small, California-based firms to produce fewer patents. Moreover, the coefficient and confidence interval extend much further into negative values than coefficients and confidence intervals applied to other variables – suggesting that, when this effect does occur, it may be quite strong. Also, the coefficient and confidence interval on SMALL_FIRM:California imply that, in 9 out of 10 comparisons with otherwise-comparable investigators, we can reasonably expect investigators affiliated with Small, California-based firms to produce more patents. Such statistics comport with the hypothesis that Small, California-based firms – some of whom are likely start-ups – pursue a patent-intensive strategy and encourage their employees to patent.

While the confidence interval applied to SubjectToCL:California still spans zero, its near-zero lower bound suggests some less likely but strong positive effect of the Compulsory Licensing provision when applied to investigators with California affiliations that are *not* small firms. The coefficient and confidence interval imply that, in perhaps in 8 out of 10 comparisons with otherwise-comparable investigators, we can reasonably expect

investigators subject to Compulsory Licensing and with California affiliations that are *not* small firms to produce more patents. Indeed, the high upper bound of the confidence interval suggests that, when the effect is observed, such investigators may produce more patents to a substantial degree. Since the effect does not apply to Small, California-based firm affiliations, the effect likely applies to affiliations with academic or government institutions based in California. Notably, prior work has found academic institutions in California to be strong patent producers relative to academic institutions elsewhere (Mowery, Nelson, Sampat, & Ziedonis, 2001).

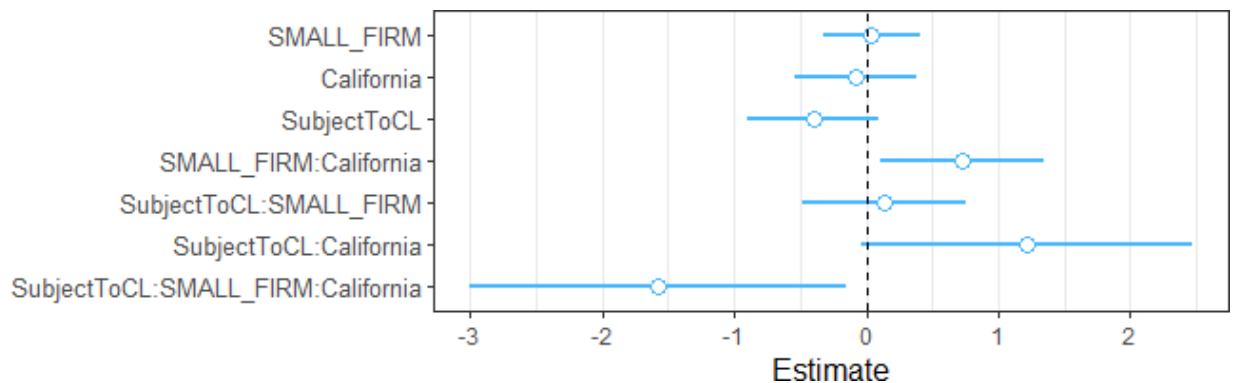


Figure 22: 99% confidence intervals for the model's coefficients applied to the SMALL_FIRM, California, and SubjectToCL variables

4.5.2.5 Large Firms and EU-based organizations

Because many members of the NGLIA (see Table 7) were large firms based in the European Union (e.g. Philips, Osram-Sylvania), the model includes interaction terms to identify the effect of the Compulsory Licensing provision on investigators affiliated with Large, EU-based firms. As would-be recipients of any patent licenses forcibly shared, the EU-based Large Firms may have given their employee-investigators subject to the Compulsory Licensing provision special direction on how to patent.

Figure 23 shows confidence intervals for the model's coefficients applied to the LARGE_FIRM, EU, and SubjectToCL variables. Aside from LARGE_FIRM (discussed in section on Large Firms based in New England), only LARGE_FIRM:EU and SubjectToCL:EU have coefficients statistically different from zero at the 99% confidence level. The coefficient and confidence interval applied to LARGE_FIRM:EU implies that, in 99 out of 100 comparisons with otherwise-comparable investigators, we can reasonably expect investigators affiliated with Large Firms based in the EU to produce fewer patents. Conversely, the coefficient and confidence interval applied to SubjectToCL:EU implies that, in 99 out of 100 comparisons with otherwise-comparable investigators, we can reasonably expect those affiliated with any EU organizations and subject to Compulsory Licensing to produce more patents.

The two statistically significant coefficients of this set offer the following interpretation. First, Large Firms based in the EU may have less interest in acquiring patents from the US Patent and Trademark Office than in acquiring patents from the European Patent Office. Perhaps due to a weaker influence in US courts, the EU firms may pursue a patent strategy that places less weight on the US patent system. Second, while the Compulsory Licensing provision may have had a positive effect on patenting for investigators affiliated with EU-based organizations, the bulk of the EU-based organizations in the sample dataset are indeed Large, EU-based firms. As such, the negative effect of being affiliated with a Large, EU-based firm would in most cases cancel out the positive effect of being subject to Compulsory Licensing while also affiliated with an EU-based firm. All together, the coefficients and confidence intervals imply that we could reasonably expect investigators not subject to Compulsory Licensing and affiliated with Large, EU-based firms to patent

less than their counterparts, and after becoming subject to Compulsory Licensing to patent *comparably with* to their counterparts.

Finally, the lack of statistical significance on SubjectToCL:LARGE_FIRM:EU suggests that the Compulsory Licensing provision had no particular effect on investigators affiliated with Large, EU-based firms. In other words, the provision brought no special effect for these investigators beyond effects already borne by their EU affiliations.

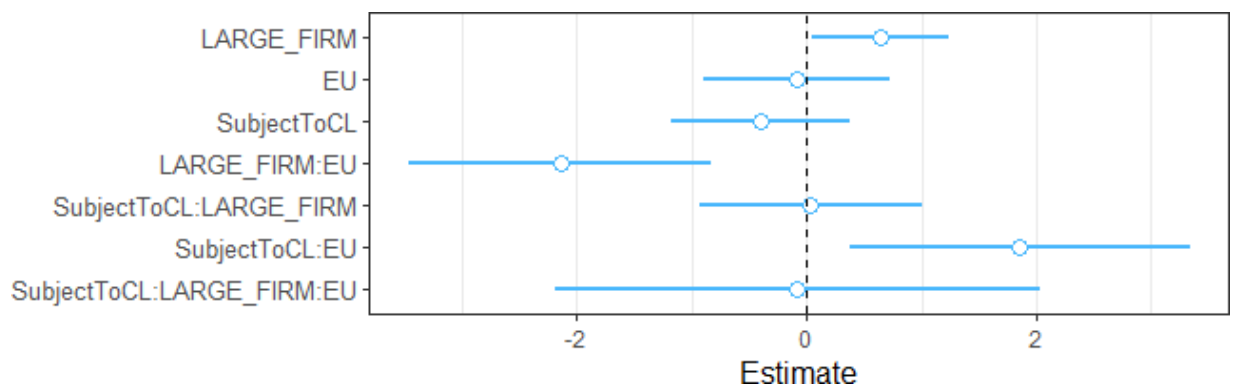


Figure 23: 99% confidence intervals for the model's coefficients applied to the LARGE_FIRM, EU, and SubjectToCL variables

4.5.2.6 Lighting sector versus Materials sector affiliations

Out of consideration for the varying importance of patents to different industries and for Teece's Appropriability Regimes framework, the regression model also includes interaction terms to capture the impact of the Compulsory Licensing provision to two very different industries – Lighting, and Materials. Of the two, Lighting clearly faces greater appropriability risks. The industry's products ship directly to the public, meaning any unknown third party can purchase and reverse-engineer a Lighting product. Moreover, the

intense patent alliances and conflicts of the Lighting industry's early history³⁸ demonstrate the relatively high (high critical) importance of patents to the Lighting industry. Conversely, the Materials industry faces lesser appropriability risks. It rarely ships products to the public, because "materials" in and of themselves have relatively little use to the vast majority of consumers. The Materials industry's products derive much of their value from the intensive processes used to engineer novel materials. Contrary to a Lightbulb, a novel material cannot be as easily disassembled, inspected, and reverse-engineered without prior knowledge of how the material was assembled in the first place (which would defeat the point of reverse-engineering the material). While the Materials industry may still use patents to defend its asset portfolio and mitigate risks, the relatively low appropriability of the industry's products make patents less important to the industry. Given these considerations, Lighting industry affiliations may have been more sensitive to the Compulsory Licensing provision and may have directed their employee-investigators to patent less after becoming subject to Compulsory Licensing. Conversely, Materials industry affiliations may not have had the same sensitivity and may have given their employee-investigators no special direction on patent production under Compulsory Licensing.

Figure 24 shows confidence intervals for the model's coefficients applied to the Lighting, Materials, and SubjectToCL variables. Only the coefficients applied to Lighting and SubjectToCL:Lighting have values statistically different from zero. Moreover, the coefficient on lighting is strong and positive, while the coefficient on

³⁸ See chapter comparing Philips and Hewlett Packard, specifically sections on Philips' early history, for a description of such examples as the Patentsgemeinschaft and the PHOEBUS cartel.

SubjectToCL:Lighting is strong and negative. All other coefficients are not statistically different from zero. The coefficient and confidence interval on Lighting implies that, in 99 out of 100 comparisons with otherwise-comparable investigators, we can reasonably expect those with Lighting industry affiliations to produce more patents. Moreover, the high strength of the coefficient and confidence interval suggest that Lighting-industry-affiliated investigators would produce between 1 and 3 patents more than otherwise-comparable investigators. The coefficient and confidence interval on SubjectToCL:Lighting implies that, in 99 out of 100 comparisons with otherwise-comparable investigators, we can reasonably expect those subject to Compulsory Licensing *and* having Lighting industry affiliations to produce fewer patents. Moreover, the extremely negative values of the coefficient and confidence interval on SubjectToCL:Lighting implies that such investigators could easily be expected to produce between 1 and 3 patents fewer than their counterparts.

The set of coefficients comports perfectly with the hypothesis that Lighting industry affiliations would exhibit greater sensitivity than Materials industry affiliations to the Compulsory Licensing provision. We see that Lighting-industry-affiliated investigators are very likely to patent more than other, comparable investigators. We also see that the Compulsory Licensing provision had a strong negative effect specifically for Lighting-industry-affiliated investigators. Taken together, the regression model implies that the Lighting-industry-affiliated investigators produced more patents than their counterparts prior to being subject to Compulsory Licensing, whose negative effect brought the patenting of Lighting-industry-affiliated investigators down to a level comparable with their counterparts. Conversely, we see no effects negative or positive for the Materials-

industry-affiliated investigators, either before or after becoming subject to Compulsory Licensing. This is exactly the behavior we expect given the greater Appropriability risks in the Lighting industry relative to the Materials industry.

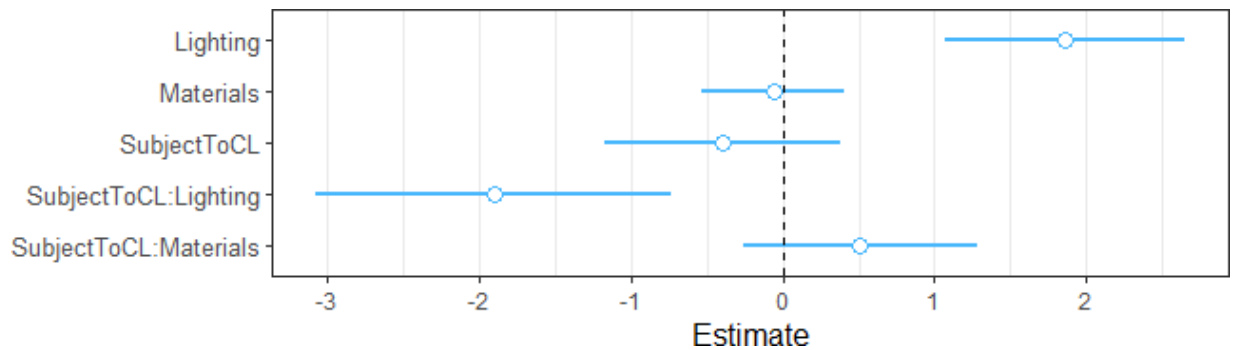


Figure 24: 99% confidence intervals for the model's coefficients applied to the Lighting, Materials, and SubjectToCL variables

4.5.3 *Summary of findings and comparisons to initial hypotheses*

Taken together, the evidence found in this study provides insights on the Compulsory Licensing provision's effects and nuanced findings for theory on Appropriability Regimes. Appropriability Regimes theory predicts that forced sharing of intellectual property, such as compelled by the DOE SSL Program's Compulsory Licensing provision, will universally reduce production of intellectual property. Conversely, this study uncovers nuanced evidence suggesting that other factors, such as a firm's size, strategy, and sector, dictate the intellectual-property-sharing policy's effects.

The findings of this study come from multiple examinations of evidence on the dataset, and Table 13 summarizes the findings in context of the study's hypotheses. Bar charts and time trends showed little noticeable difference in patenting between investigators with small firm affiliations and investigators with large firm affiliations. Fitting of an optimal

regression model and analysis of the model statistics showed no effect coming solely from Large Firm affiliations or Small Firm affiliations alone. Rather, several other factors played a strong role in moderating the effect of Compulsory Licensing on patenting behavior. Affiliation with a sector facing high Appropriability risk, such as the Lighting sector, produced a strong negative effect on patenting when the investigator was under Compulsory Licensing. Affiliation with a Small Firm from California, likely to be an intellectual-property-focused start-up, produced a less robust but similarly strong negative effect on patent production when under Compulsory Licensing. Conversely, affiliation with a Small Firm from California without Compulsory Licensing produced a strong positive effect on patenting. Being affiliated with a non-Large-Firm organization from New England produced a strong positive effect on patenting regardless of whether the investigator was or was not subject to Compulsory Licensing.

Table 13: Summary of hypotheses and findings of the study

| Hypothesis | Finding | Relevant Evidence |
|--|----------------|---|
| <i>H1: The compulsory licensing policy decreased patenting among inventors whose work was funded by the DOE SSL program</i> | Reject | Regression shows insignificant effect of being subject to the compulsory licensing policy alone |
| <i>H1a: The compulsory licensing policy reduced the patenting of researchers at smaller firms more than the patenting of researchers at larger firms.</i> | Reject | Regression coefficients near zero for both Small and Large firm affiliations; time series and bar charts show no obvious difference |
| <i>R1: The compulsory licensing policy had no effect on inventors whose work was funded by the DOE SSL program</i> | Fail to reject | Regression shows insignificant effect of being subject to the compulsory licensing policy alone |
| <i>R2: Any observed differences between researchers subject to the compulsory licensing policy and researchers not subject to the compulsory licensing policy are due to age differences between the two groups and not to the effects of the compulsory licensing policy.</i> | Reject | Regression shows no significant effect of the proxy for age, “years since earliest data,” i.e. there is no significant effect of age on patenting in this sample |
| <i>H2: The compulsory licensing policy decreased patenting by researchers facing high Appropriability Regimes more than it decreased patenting by researchers facing low Appropriability Regimes in the industries of the researchers’ respective firms.</i> | Fail to reject | Regression shows strong negative effect for Lighting industry affiliations under Compulsory Licensing, and strong positive effect before Compulsory Licensing; regression shows no effect for Materials industry affiliations |

4.6 Conclusions

Overall, the study’s evidence from sampled researchers’ patenting behavior indicates support for a path-dependent explanation for reduced patenting in the face of a policy

designed to spread knowledge embodied in patented technologies. Teece's Appropriability Regimes hypothesis holds and provides part of the explanation, but there are further nuances – specifically with regards to which sector a researcher is working in. As with related path-dependency studies, the path-dependency focus helps highlight factors that have contributed to countervailing effects against policy design and, in so doing, aid the design of more effective policies for change.

From this study, the relevance of path-dependency to the specific case of the DOE SSL program is abundantly clear. The DOE SSL program reflects path-dependency by being grounded in the R&D environment of its origin and through the program's innovative patent policy, which works against a broader path-dependency of policies supporting patent rights and protections. While the DOE SSL Compulsory Licensing policy sought to encourage sharing of R&D-produced knowledge by compelling the sharing of patents, much prior US policy toward patents discouraged patent sharing and encouraged US federal agencies to allow researchers to retain patents. Specifically, in response to challenges from non-US firms and policies implemented by non-US governments, the US R&D industry successfully pressed throughout the 1980s for an array of new policies towards patents. The Bayh-Dole Act, the Federal Technology Transfer Act, the National Competitiveness Technology Transfer Act, and the Stevenson-Wydler Technology Innovation Act represent examples of the US R&D system's patent policy transition. Concurrently, non-US governments implemented their own patenting policies and made patent policies a major issue during WTO negotiations. Moreover, the DOE SSL program's design reflects its origins in a highly competitive and cross-institutional R&D business environment. The DOE SSL program came into existence in a new era of global R&D

competition; R&D performance by universities, small firms, and government laboratories; industry-academic-government alliances; and complex intellectual property configurations. Given the SSL Program's environment, the SSL Program facilitated cooperation from large, established firms and R&D performance by universities, small firms, and government laboratories through a complex patent policy. Fulfilling Nelson and Winter's hypothesis, the design of the DOE SSL Program reflected a newfound environment of global R&D competition and advocacy for intellectual property rights. Moreover, the program's design triggered participation from certain firms that had succeeded in the pre-World-War-I era of global R&D competition and complex patent arrangements.

4.6.1 Conclusions on compulsory licensing's interaction with Appropriability Regimes

The study begins with an apparent conflict between policy design and prior findings but ends with a conclusion that suggests refinement to both policy and theory. The DOE SSL program's compulsory licensing policy motivated the research question of the policy's impacts on funded researchers, as prior literature indicates that reducing the freedom of patent-holders to license patents as they may wish would reduce the incentives for researchers to produce patents. In particular, Teece's work on Appropriability Regimes suggests that when patent protections are reduced through compulsory licensing policies, researchers will become less likely to patent technologies that are easier to reverse-engineer. Taken together, however, the evidence found in this study provides insights on the Compulsory Licensing provision's effects and nuanced findings for theory on Appropriability Regimes. From patterns in the sampled researchers' patent production, especially a reduced level of patenting by researchers in the lighting sector relative to

researchers in the materials sector, the analysis concludes that path-dependent variables influenced the extent to which patenting was affected by the compulsory licensing policy.

The study also finds a strong role for path-dependent factors in explaining the observed outcomes and providing a broader perspective on designing policy to foster sector-specific innovation. Teece's Appropriability Regimes work predicts that forced sharing of intellectual property, such as compelled by the DOE SSL Program's Compulsory Licensing provision, will universally reduce production of intellectual property. Conversely, this study uncovers nuanced evidence suggesting that other path-dependent factors, such as a firm's size, strategy, and sector, dictate the intellectual-property-sharing policy's effects. In particular, the data showed that the path-dependent affiliation of a researcher with a sector facing high reverse-engineering risk, such as the Lighting sector, exhibited a strong negative effect on patenting when the investigator was under Compulsory Licensing. Similarly, the researcher's path-dependent affiliation with a Small Firm from California, likely to be an intellectual-property-focused start-up, produced a less robust but similarly strong negative effect on patent production when under Compulsory Licensing. The path-dependent factors of affiliation with a given sector and the amount of reverse-engineering risk a sector's technology faces appeared to have played a strong countervailing role to the knowledge-sharing effect of Compulsory Licensing intended by the policy.

4.6.2 Conclusions on path-dependency's lessons for lighting R&D policy

The study highlights the relevance of path-dependency concepts to innovation in lighting R&D policies. The studies highlight that innovative R&D and energy policies often stand

against strong path-dependencies, as much or more so than technologies for R&D and energy sectors. Furthermore, the studies reviewed also show how a path-dependency framework would identify relationships within the R&D and energy policies studied in this dissertation. Applied to the R&D and energy policies, path-dependency highlights the following:

1. Policies generally assume the existence of actors whose behaviors the policy wishes to change. In this case, the actors are individual researchers and the wished-for behavioral change is increasing knowledge-sharing.
2. The behavior of these actors is influenced by certain key variables, and the policy in question aims to manipulate these key variables. In this case, the key variables are patent protections afforded under Bayh-Dole Act policies and attempts at manipulating key variables are the program's Compulsory Licensing policy.
3. The policy in question does successfully manipulate the targeted key variables. In this case, the policy mandates patent licensing negotiations.
4. However, the successful manipulation of key variables by the policy does not ultimately lead to behavioral change because of extant, path-dependent variables. In this case, the extant path-dependent variables are the Appropriability Regimes faced by inventors in different sectors.
5. In highlighting the extant variables in part (4) above, the path-dependency framework helps us understand that policies to promote knowledge-sharing should account for extant path-dependent variables such as Appropriability Regimes may affect knowledge-sharing, such

as by promoting knowledge-sharing through other means such as joint-ventures, MOUs, and other collaborative partnerships.

The study's use of a path-dependency framework highlighted path-dependent variables such as Appropriability Regimes that fluster innovative R&D policies. The study illustrates the influence of path-dependency on outcomes from innovative policies stimulating innovation in the lighting sector. By applying path-dependency to patent licensing requirements, the study builds upon prior findings in path-dependency. In highlighting factors that frustrate the aims of contemporary innovation policies towards lighting, this dissertation aims to inform the design of future innovation policies such that future policies may account for influential factors and design strategies that nullify or take advantage of such factors to enact change.

As with any study of path-dependency, the overall finding must be one of nuance. A policy attempting to force sharing of patents may not necessarily discourage patent production in every case, but may have disparate impacts among those affected because of path-dependent factors governing patent production. Theory predicted that the forced sharing of patents would discourage the affected parties from producing patents, but only in certain cases did this turn out to be true. We can conclude, for example, that if the DOE SSL Program expected technology expedition to occur through forced sharing of patents produced by Lighting-industry-affiliated investigators, the program may have defeated itself through a policy that discouraged Lighting-industry-affiliated investigators from producing patents. Conversely, if the DOE SSL Program held the same expectation for Materials-industry-affiliated investigators, the program may rest easy knowing that its Compulsory Licensing policy is not likely to have defeated this goal. Moreover, if the

program hung its hopes on patents produced by Small Firms, the program needn't worry – unless the program had specifically hoped for small, California-based startups to acquire and then share patents. This study has revealed many such nuances in the relationship between policies for forced patent sharing and affected parties' decisions to produce patents. The study underscores the fact that path-dependency concepts help researchers understand the factors and patterns that have contributed to persistent circumstances and in so doing aids the design of more effective policies for change. The study uses a path-dependency research lens to highlight factors that an innovative policy effort did not capture and aids in the crafting of more effective means of creating change.

4.6.3 Who should care and why

Policymakers who design policies to affect patenting and particularly the sharing of patents and other forms of intellectual property and academics who the patenting behaviors of individual inventors should care about this chapter because it reveals nuances in how Appropriability Regimes interact with patent policies to influence patenting. Since this chapter's analysis reveals a key factor affecting inventors' patenting behavior, policymakers and academic researchers focusing on this area should alter their policy designs and research designs accordingly. A policymaker should assess the type of Appropriability Regime faced by the industry whose R&D sharing practices the policymaker seeks to affect. If the Appropriability Regime is strong, policies encouraging patent-sharing may not be a good means of encouraging overall R&D sharing. Conversely, if the Appropriability Regime is weak, encouraging patent-sharing may result in the actual sharing of more patents – with the caveat that most key R&D under a weak Appropriability Regime might not be captured in patents. Considering this caveat, the policymaker facing

a weak Appropriability Regime should consider other means of encouraging R&D sharing, such as requiring personnel transfers or encouraging joint-ventures. An academic researcher seeking to understand the drivers behind individual inventors' patenting behavior should take care to assess the Appropriability Regime faced by the industry of the inventors the researcher is studying. Inventors facing a weak Appropriability Regime might produce fewer patents, and vice-versa, as the inventors may judge the importance of producing patents to be in proportion to the Appropriability Regime of the inventors' industry. Also, publishing academic researchers' assessments of the Appropriability Regimes at work in different industries would be of value to policymakers seeking to affect patenting behavior.

CHAPTER 5. PATH-DEPENDENCIES IN LIGHTING TECHNOLOGY AND ELECTRIC POWER INFRASTRUCTURE

5.1 Research question

This chapter addresses the question of whether SSL-driven lighting innovation and policy goals seeking societal benefits from lighting technology adoption can be interfered with by differences in regional energy infrastructures. Policymakers who seek broad societal benefits through SSL-driven lighting innovation are usually banking on how the SSL lighting technology interacts with electric power infrastructure. While SSL technologies have many advantages, the most touted and most often pursued by policies seeking SSL technology development and deployment is SSL's energy efficiency. SSL's energy efficiency contributes to public health and climate change mitigation by reducing carbon dioxide and other air pollution emissions from the electric power sector. By using less electric power to generate the same amounts of light used by various applications, SSL energy efficiency can assist these policy goals. However, this logic necessarily implies a dependency on existing energy infrastructure for SSL to have societal benefits. In particular, SSL interacts with air pollution and CO₂ emissions through the buildings in which SSL devices are installed and through the electric power infrastructure servicing those buildings. If SSL technology is installed in buildings where lighting is not used very much, for example, SSL may not deliver much energy savings and emissions reduction. Similarly, if those buildings are serviced by a grid powered mainly by zero-emitting resources, SSL installations may not deliver very much emissions reduction. As such, there is reason to question the extent to which SSL technology can transform societal outcomes.

To examine the extent to which SSL technology transforms societal outcomes, the analysis reports on a simulation study calculating the effects of expanded SSL device adoption under climate regulations on the electric power sector. Through the now-repealed US Clean Power Plan, the US had aimed to restrict the level of greenhouse gas emissions from the US electric power sector and encouraged US states to use energy-efficient consumer technologies to do so. Literature on the relationship between electric power sector outcomes and efficient energy-consuming technologies identifies several hypotheses on how SSL adoption might affect electric power consumption and production. The analysis compares outcomes from empirically grounded simulations of four geo-economic regions under scenarios of Clean Power Plan compliance with and without a subsidy for LED technologies. Results calculated from the simulations reveal to the intervening role of extant infrastructure present in each of the four regions, which moderates the effect of the adopted LED technologies. The chapter reaches conclusions regarding the role of path-dependency in the context of electric power infrastructure and lighting technology innovation and offers conclusions and guidance for future policymakers.

5.2 Literature Review

The Clean Power Plan's recognition of energy efficiency – and by extension, SSL – as a valuable option for reducing the electric power sector's CO₂ emissions is supported by a wide range of literature. The amount of energy savings achievable through energy efficiency measures, as well as the associated CO₂ emissions reductions, has been exhaustively studied. Wang & Brown (2014) provide an overview of this copious literature, which generally finds that energy efficiency measures provide cost-competitive options for reducing CO₂ emissions and in substantial amounts (see also Brown & Sovacool, 2014).

Wang and Brown focus on standards, financial incentives, and information programs for promoting energy efficiency that specifically target residential, commercial, and industrial customers of electric power utilities. (M. A. Brown & Li, 2019) examine the extent to which policies toward demand-side technologies can complement the goals of carbon tax policies toward other sectors – including the electric power sector. (M. A. Brown, Kim, & Smith, 2016) make a similar study for carbon policies toward the electric power sector alone. (Rogelj et al., 2015) find energy efficiency to be a crucial instrument for meeting current goals of keeping global warming below 1.5 degrees Celsius by 2100. (M. A. Brown, Levine, Romm, Rosenfeld, & Koomey, 1998) compare demand-side options with supply-side options for reducing greenhouse gas emissions, finding demand-side options to be more cost-effective. Hanson & Laitner (2004) compare the impacts of investment in energy-efficient technologies against the impacts of a carbon tax between \$48 to \$98 per metric ton.

Despite this literature on the relationship between CO₂ emissions from the electric power sector and energy efficiency, however, a literature gap exists regarding the role of energy efficiency and specifically SSL in compliance with the electric power sector's CO₂ emission regulations. As highlighted in Brown, Kim, Smith, & Southworth (2017), prior analysis of energy efficiency as an option for complying with CO₂ emissions regulation for the electric power sector, such as the Clean Power Plan, has been poor. For example, representation of energy efficiency in prior studies of Clean Power Plan compliance was so primitive as to hardly constitute attempts at representing energy efficiency at all. Because of the limitations of their models, some studies have ignored energy efficiency entirely when examining options for mitigating the electric power sector's greenhouse gas

emissions (Peters & Hertel, 2017). Other studies have taken crude and inadequate approaches to representing energy efficiency, such as assuming that energy demand is somehow mysteriously and exogenously reduced at some lump-sum cost to society. Such approaches obviously fail to answer the question of how the reductions are achieved and what implications those reductions have for the portfolio of technologies used to consume energy by the residential and commercial sectors. Moreover, such modeling approaches cannot reflect instances when supply-side investments for meeting greenhouse gas reduction requirements elevate electricity prices and make energy-efficient technologies, like LED-based lighting, more attractive to end-use consumers.³⁹ Many studies use such inadequate models and approaches, attempting to make sweeping statements about energy policy without considering granular realities, including examples such as:

- Integrated Planning Model (IPM) used by US Environmental Protection Agency (2014), MJ Bradley & Associates (2016), and the Bipartisan Policy Center (2016)
- the Haiku model used by Resources for the Future (Burtraw, Linn, Palmer, & Paul, 2016),
- US-REGEN used by the Electric Power Research Institute (2016)
- FACETS-ELC used by Wright & Kanudia (2016)

While Brown et al. (2017) fill a crucial gap in rigorously modeling energy efficiency as an option for Clean Power Plan, their analysis fails to include any specific examination of the compliance role for SSL. Moreover, Brown et al.'s use of the EIA 2015 AEO High Tech

³⁹ For further detail on the design and advantages of GT-NEMS, consult (Brown, Kim, Smith, and Southworth, 2017)

case assumptions fails to provide a data-grounded characterization of LED technologies and also fails to capture recent forecasts of LED product cost and performance – i.e. using outdated information to represent SSL. As such, a literature gap exists regarding the role of SSL products in compliance with CO₂ emissions reduction policies for the US electric power sector.

Despite the established relationships between emissions reductions and efficient technologies in lighting and other consumer technology sectors, the literature still leaves questions open and gaps between known influential factors and reports on modeling. For example, while Brown et al., 2017 makes a general finding that energy efficiency reduces power sector operating costs under the CPP, that study applies that finding to the nation as a whole and fails to consider the significant heterogeneity across regions of the US. Power sector infrastructure varies significantly across US regions. For example, the Pacific Northwest is primarily powered by hydroelectric dams, while California is now powered almost entirely by natural gas, wind, and solar generators. Moreover, the portfolio of buildings into which adopted LEDs would be installed varies significantly between regions as well. Building codes vary considerably from state to state, with California codes requiring significantly more energy-efficient designs than southeastern building codes, for example. Buildings are designed with local climates in mind as well as such the lesser average insulation in a California home reflects the more temperate Pacific climate while the greater insulation in a Minnesota home reflects the harsh winters of the Upper Midwest. As such, there is good reason to expect that increased adoption of energy-efficient consumer technologies would have differing impacts from region to region within the US. Moreover, a finding of a relationship between energy-efficient consumer technologies and

power sector costs may mask true relationships at the regional level, since the national level outcomes are simply aggregations of outcomes at the regional level.

5.3 Hypotheses

As the literature identifies strong relationships between electricity consumption, the electric power sector's CO₂ emissions, electric power capacity construction, and deployment of energy-efficient consumer technologies like SSL, the literature lends several hypotheses to this study. This section lays out hypotheses that guide the remainder of the study.

5.3.1 Hypotheses 1: Sectors whose building types are the most intensive users of lighting will exhibit the greatest LED adoption

Given the direct relationship between energy costs, energy consumption, and use of energy services, it follows that sectors using a great deal of lighting service have the most money to save from installing LEDs. In particular, sectors whose buildings use the most lighting per square foot seem best-positioned to take advantage of LEDs' energy efficiency. Intensive use of lighting within a building creates greater electric power consumption, which in turn creates high electric utility bills; adopting LEDs allows such buildings to maintain the same intensive use of lighting while lowering electricity consumption.

Figure 25 provides data from the EIA's Commercial Buildings Energy Consumption Survey (CBECS), showing each building type's percentage of illuminated floorspace. From the EIA data, Healthcare, Food Sales, and Education appear to be the sectors whose building types use the most lighting. As such, a reasonable hypothesis would be to find that

these building types consistently rank near the top of LED adopters in the forecast. Moreover, it's further reasonable to hypothesize that the building types will show the same rank in LED adoption as they do for intensity of lighting use.

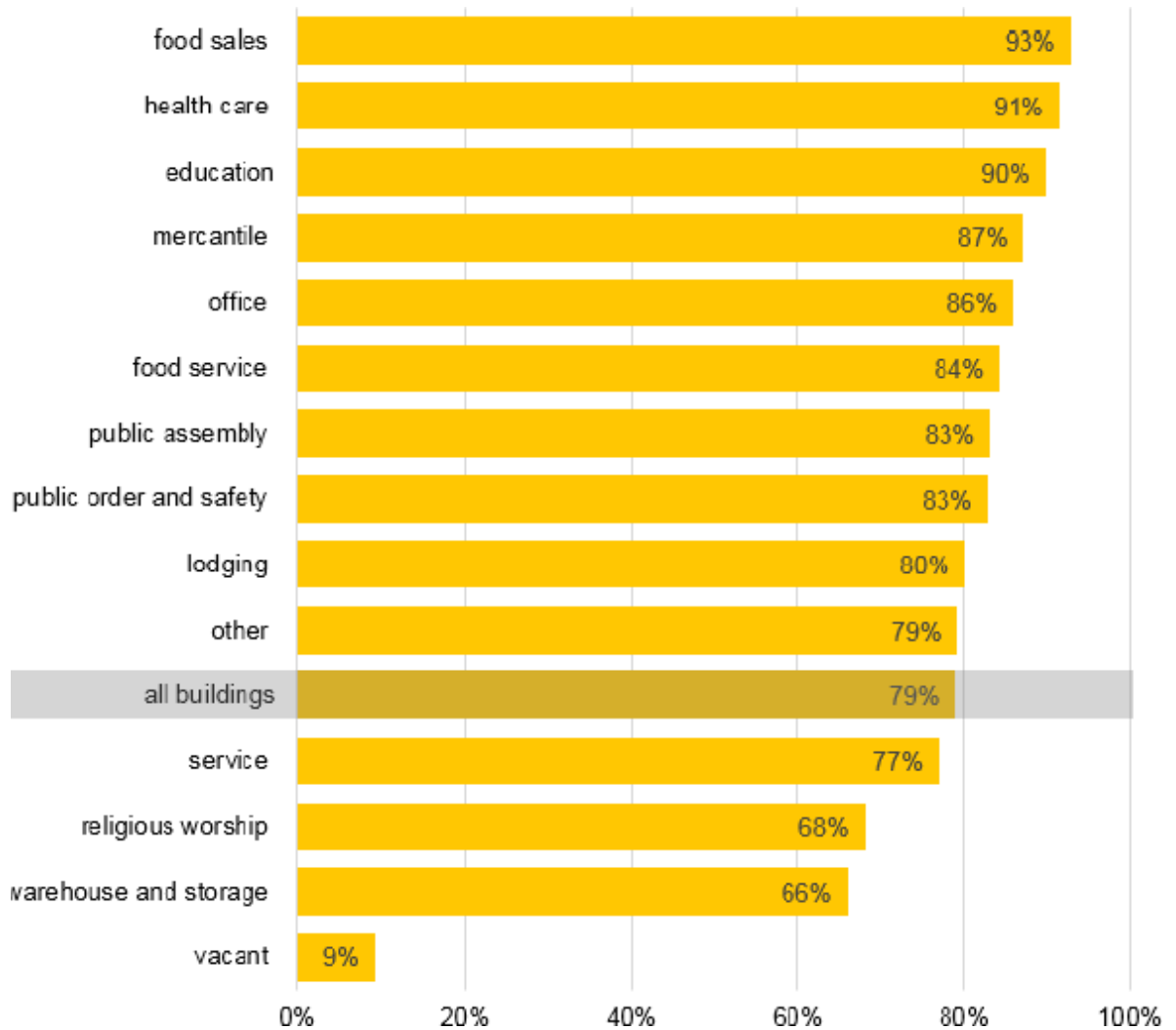


Figure 25: Percent of illuminated floorspace (x-axis) by building type (y-axis).
Source: US Energy Information Administration, 2017

5.3.2 *Hypothesis 2: Holding LED adoption constant, power sector outcomes will vary by region due to the influence of path-dependent factors*

From the literature on path-dependency, the importance of the path-dependent context in which policies toward electric power consuming technologies for lighting services operate seems particularly relevant. The study possesses key tenets of a path-dependent situation: A policy here LED subsidies – may intend to manipulate outcomes – here costs, pollutants, or renewable power generation – by way of manipulating intermediate variables – here technology cost, which subsequently influences technology choice and ultimately electricity consumption. In spite of this causal relationship, however, there are other path-dependent variables – here the regional electric power infrastructure – that also influence the intermediate variables that the LED subsidy policy may not account for. Moreover, electric power infrastructure is extremely path-dependent because it cannot easily be transmuted or reversed or converted into new infrastructure.

Many examples exist of how extant factors may affect the power sector impacts of adopting LEDs. A small set of such examples includes:

1. Location of the LEDs on the power grid – if LEDs decrease load at a bus from which power already is net-flowing away (such as in upstate NY, in which power flows toward NYC), this may not matter much for regional capacity building since that capacity is built to serve peak load of the region (which in NY is NYC)
 - a. Moreover, load that balances a congested set of power lines is actually useful for reducing the amount of new generating and transmission capacity necessary to meet demand overall – thus reducing load at such an “upstream” bus (i.e. a bus proximal to generation) actually exacerbates the

need for transmission capacity, begetting further transmission investment and therefore increasing costs to consumers

2. Fuel of generating portfolio – If LEDs are deployed in regions served largely by renewable or low-emitting power generating units, the LEDs will not result in as much of a reduction in emissions of harmful pollutants as they would if deployed in a region served by high-emitting power generating units.
3. Long term power purchase agreements – even if LEDs reduce power demand in a given municipality, for example, the municipality in which LEDs are installed may have a long-term agreement (e.g. 10-year power purchase agreement) to purchase power from a high-emitting source and may choose to simply re-sell the purchased power it no longer needs. If this happens, the high-emitting source’s output remains unchanged despite LEDs successfully reducing power demand. Worse yet, the municipality may have a take-or-pay contract with the high-emitting generator and may have to pay for any reductions in purchased power – meaning that LEDs would reduce power demand but increase costs to consumers.
4. Lighting use in buildings – if LEDs are installed in buildings that already do not use much lighting, per unit space and time, the overall impact on power demand will likely be minimal.
5. Planned expansions of transmission or generating capacity – if infrastructure buildout is already planned for an expected increase in demand, LEDs may only defer rather than mitigate such expansions (and associated emissions). Deferral

may still have value but will fall short of meeting any policymaking goals to avoid completely the need for new infrastructure.

Entities in the power sector have recognized the connection between demand-side energy efficiency and their operations and have developed various treatments of end-use efficiency in their strategic planning documents. In particular, major utility companies have brought their thinking to bear on this problem by trying to incorporate energy efficiency investments, such as LEDs, into their strategic investment planning. As one example, the Tennessee Valley Authority (TVA)'s efforts in developing its 2015 Integrated Resource Plan (IRP) attempted to treat energy-efficient demand-side technologies as a resource similar to a power plant. Investments in deploying energy-efficient demand-side technologies were aggregated into 10MW blocks and assigned various power-plant-like parameters, such as daily output profiles, capacity factors, and construction costs (Marilyn A. Brown & Wang, 2015; Rice, 2016). Pacific Gas and Electric (PG&E)'s 2018 IRP implemented an alternative approach to integrating energy efficiency into the utility's strategic planning. Instead of offering rebates and other subsidy-like incentives to customers purchasing efficient lightbulbs, as one example of a "widget-based" strategy common across many utilities, the utility now offers performance-based incentives that reward customers in direct proportion to actual energy saved (Pacific Gas and Electric, 2018). In its Energy Efficiency Business Plan, a strategic planning document dedicated specifically to the company's demand-side energy efficiency investment strategy, PG&E outlines expectations that such performance-based programs will do more to ensure actual energy efficiency gains and incentivize customers to go beyond the "widget-based" gains

by creating synergies between devices and changing energy consumption behavior (Pacific Gas and Electric, 2017).

This path-dependency cannot be ignored and should inform our expectations of the results. It's reasonable to hypothesize that, to any given level of LED adoption, regions with their own path-dependent infrastructure should respond differently. We should find both qualitatively different and quantitatively different outcomes for each region, despite any similarities in their levels of LED adoption.

5.3.3 Hypothesis 3: Greater LED adoption results in lower Total Resource Cost

Given the cost savings associated with LED adoption and the low cost of the “negawatts,” provided by efficient technologies, it follows that all regions should experience reductions in Total Resource Costs under a scenario with high LED adoption. By reducing electric power demand, LEDs provide an opportunity to reduce costs to the electric power sector of meeting new or existing demand – and all the more so when the costs are augmented by constraints such as those imposed by the Clean Power Plan. Importantly, the definition of Total Resource Cost captures only the costs to the electric power sector, including compliance with policies such as the Clean Power Plan. As such, any cost to government for e.g. a subsidy would be excluded from Total Resource Cost calculations.⁴⁰ As such, it is reasonable to hypothesize that any level of LED adoption can result only in reductions in Total Resource Costs, and that scenarios with greater LED adoption should always exhibit lower Total Resource Costs than scenarios with lesser LED adoption.

⁴⁰ The TRC does include the costs of utility-funded energy efficiency programs, but not the cost of programs directly funded by federal, state, or local governments.

5.3.4 Hypothesis 4: Greater LED adoption displaces high-emitting power sources

Because the Clean Power Plan requires regions to reduce emissions from the power sector, LED adoption will enable regions to meet Clean Power Plan emissions reduction demands at lower cost and enable regions to displace high-emitting power sources, which tend to be older and more expensive to operate. As such, it seems reasonable to hypothesize that LED adoption will primarily displace high-emitting resources like power plants that use coal-fired and oil-fired steam turbines. Moreover, it seems unlikely that LED adoption will displace clean generators like Renewables and Combined Cycle generators because of the premium the Clean Power Plan creates for those resources. The Clean Power Plan creates opportunities for relatively low-carbon-intensive capacity, and it seems reasonable to hypothesize that LED adoption will augment those opportunities by displacing primarily heavy greenhouse gas emitters.

5.4 Methodology for testing hypotheses

To examine interplay between LED adoption and power sector emissions regulations, we use the computational general equilibrium model GT-NEMS to compare LED adoption outcomes to electric power sector cost and capacity outcomes under a scenario of CPP compliance with a subsidy to LED technologies. We use a scenario of subsidy to LEDs under CPP compliance to increase LED adoption throughout the simulated economy and observe impacts on the power sector's costs as represented by TRC metrics. TRC metrics include both operational expenses and costs related to financing and investment and are a common metric for the cost impacts of energy-efficient consumer technologies. Because the examined regions achieve CPP compliance both in the scenario with the LED subsidy

and the scenario without the LED subsidy, the total emissions reductions achieved remain constant while the costs of compliance and power sector operations vary across scenarios. By holding the total emissions reduced constant and allowing compliance costs to vary, we can make inferences about what relationships additional LED adoption has on the cost of CPP compliance and power sector operations. Moreover, we can compare the relationships between LED adoption and compliance costs across the examined regions. To make the appropriate comparisons, the analysis will compare LED adoption within the four regions of interest, expecting similarities between the regions in terms of increased total LED adoption under the LED subsidy. The analysis will also explore distribution of adopted LEDs within the four regions, particularly across building types within each region's commercial building portfolio. Then, the analysis will examine regional TRC outcomes, highlighting both changes in power sector operating costs within each region and comparing across the regions, as well as comparing to the regions' LED adoption. The analysis will search for difference and data that explain how two or more regions adopting similar levels of energy-efficient consumer technologies while complying with the CPP can exhibit significant differences in power sector cost outcomes.

While most studies of electric power sector emissions apply different policies to observe emissions reductions outcomes, this study takes a novel approach by holding emissions reductions constant and observing variation in compliance costs under different scenarios. By allowing the examined regions to achieve CPP compliance in all scenarios and allowing compliance costs to vary by scenario, the study exposes relationships LED adoption has with the cost of CPP compliance and power sector operations. Finally, while the literature generally finds that efficient energy-consuming technologies provide cost-competitive

options for reducing CO₂ emissions, the analysis presented here adds nuance by illustrating heterogeneous, path-dependent, region-specific impacts of introducing efficient technologies. The study's comparison of regional LED adoption to Total Resource Cost (TRC) and electric power capacity outcomes under CPP compliance with a subsidy to LED technologies reveals the regional differences that nuance nation-level findings, such as that presented in Brown et al. (2017).

5.4.1 Using GT-NEMS to model power sector and consumer sector interactions

To estimate the impacts of subsidies for SSL lighting products upon electric power infrastructure under a greenhouse-gas emissions reduction policy, I use a computational general equilibrium model called GT-NEMS. GT-NEMS is a modified version of The US DOE's National Energy Modeling System (NEMS), which models the U.S. energy economy and calculates a cost-minimizing resource investment strategy for meeting energy demand. The differences between NEMS and GT-NEMS lie entirely in the computer systems necessary to run NEMS on Georgia Tech computer systems. As such, GT-NEMS retains all of NEMS' calculations and is functionally equivalent to NEMS, and hereinafter references to NEMS also refer to GT-NEMS and vice-versa. NEMS has been widely used by energy researchers for addressing important policy questions, including whether the US should ratify the Kyoto Protocol (M. a Brown, Levine, Short, & Koomey, 2001). The US DOE also uses NEMS annually to generate a three-decade forecast of the US energy economy called the Annual Energy Outlook. The version of GT-NEMS used in this study

is based on the version of NEMS that generated the 2015 Annual Energy Outlook (US Energy Information Administration, 2015).⁴¹

GT-NEMS comprehensively represents the US energy economy through representing multiple sectors and their interactions. GT-NEMS represents four sectors, each computationally represented by its own module, that constitute US energy demand: residential, commercial, industrial, and transportation. GT-NEMS also represents four sector-modules for US energy supply: oil and gas, gas transmission, coal, and renewable fuels. GT-NEMS also represents via modules two US energy conversion sectors: electric power, and petroleum products. GT-NEMS also represents international energy supply and demand through an international module. GT-NEMS represents macroeconomic impacts on the US energy economy by using a macroeconomic model provided by IHS Global Insights, and GT-NEMS represents relationships between the sectors via an integrating module.

Because this study focuses on SSL lighting technologies, the study focuses on the calculations made by GT-NEMS' electric power module and commercial buildings module. GT-NEMS' commercial buildings module offers comprehensive representation of technologies for meeting many energy services demanded by residential and commercial sectors. For example, the commercial module represents multiple kinds and vintages of both electric and natural gas technology options for providing space heating. Through sets of cost and performance parameters, the commercial buildings module represents an array of lighting technologies that the modules select from in order to minimize cost of meeting

⁴¹ Comprehensive documentation of the GT-NEMS/NEMS calculation methodologies and computational structure can be found on the US DOE Energy Information Administration's website:

demands for light. The commercial buildings module includes LED-based lighting technologies, allowing LED-based technologies to compete with incumbent and conventional lighting technologies such as filament bulbs and fluorescent tubes.

Moreover, GT-NEMS includes parameters to reflect the “rebound effect” of deployment of energy-efficient technologies, i.e. the marginal increase to energy consumption that may occur because an energy-efficient technology makes energy consumption less costly to the consumer, leading the consumer to use the technology more and consume marginally more energy. GT-NEMS calculates the rebound effects of energy efficient products on energy consumption through the following formula:⁴²

$$E_{EnnddUUseeCCoonssuumppff,ss,bb,rr,yy} = E_{EnnddUUseeCCoonssuumppff,ss,bb,rr,yy} \cdot KKEEllaassttf,rr,yy,ss \\ \cdot [1 + [1 - A_{AvveerraaggeeEEffffiicciienccyyr},, / A_{AvveerraaggeeEEffffiicciienccyyBBAASSErr,bb,ss,ff}] \cdot \epsilon_2 \\ \cdot (1 + [S_{SheelllEEffflInnddeexbb,rr,ll}] \cdot \epsilon_2)$$

In which:

- $E_{EnnddUUseeCCoonssuumppff,ss,bb,rr,yy}$ is the projected consumption of fuel by end-use service, major fuel, building type, Census division, and projection year
- $KKEEllaassttf,rr,yy,ss$ is the graduated short-term price elasticity function. Elasticity for a given major fuel, end-use service, and Census division in a given year is calculated as a weighted function of the price of the given fuel in the current year and the previous two years relative to the fuel price in CBECS year

⁴² This formula is taken from the NEMS 2013 documentation for the Commercial module and is indexed as Formula B-109

- $AAvveerraaggeeEEffffiicciieennccyy_{rr,bb,ss,ff}$ is the effective average efficiency of the equipment mix by major fuel, end-use service, building type, and Census division for the current year, as calculated in the Commercial module's "Technology Choice" subroutine
- $AAvveerraaggeeEEffffiicciieennccyyBBAASSEE_{rr,bb,ss,ff}$ is the effective average efficiency of the equipment mix by major fuel, end-use service, building type, and Census division during the CBECS base year, as calculated from the input equipment efficiencies and market shares
- $SSheellllEEfffflInnddeexx_{bb,rr,ll}$ is the heating or cooling building shell efficiency factor for the current Census division, building type, and year
- ϵ_2 is the parameter representing price elasticity due to rebound effect, currently set at -0.15

In its essence, the formula above increases energy consumption whenever the average efficiency of the current scenario is greater than the average efficiency of the base case, and decreases consumption whenever the reverse is true. The second term in the formula, which applies to lighting (the third term does not and only applies to space heating/cooling), takes the marginal increase or decrease in efficiency between the current scenario and base case scenario and multiplies that increase or decrease by -0.15. This means that 15% of the marginal increase (decrease) in efficiency gets added to (subtracted from) total energy consumption. Debates over the proper rebound magnitude assumptions have raged for years (Sorrell, Dimitropoulos, & Sommerville, 2009), with some arguing that rebound is underestimated (Fronzel & Vance, 2013) and others arguing that rebound

is overestimated (Gillingham, Kotchen, Rapson, & Wagner, 2013). Simulations and theoretical works tend to predict high levels of rebound, such as an over 100% rebound effect calculated by Hicks & Theis (2014). Conversely, empirical works tend to observe lower levels of rebound, such as the 2% effect reported by Gillingham et al. (2013). Despite these debates, GT-NEMS' representation of the rebound effect is on par or even overly conservative relative to recent work providing empirical estimates of rebound effects for lighting. For example, a 6% rebound effect was recently calculated from a representative survey of households that installed more efficient lighting products (Schleich, Mills, & Dütschke, 2014).

In representing lighting products, GT-NEMS also offers the advantage of representing the load profile of lighting technologies in different building types. The term “load profile” refers to how much power a given technological device will consume over the course of a day. Because electric power must be generated at the exact moment it is needed, electric utility strategic planning makes use of load profiles to understand when electric power demand is likely to increase and decrease over the course of a day. The load profiles of individual technologies are aggregated into a system-wide load profile representing the hourly distribution of electricity demand. The system-wide load profile in turn informs utility planners in many decisions, including for example how much fast-ramping capacity (i.e. power plants that can quickly increase or decrease output) is needed. GT-NEMS provides load profiles for every technology powered by electricity. Beyond this, GT-NEMS offers even greater granularity by offering different load profiles for each building type. In other words, GT-NEMS will represent an LED product installed in a warehouse with a different lighting load profile than that of an LED product installed in a small office

space. Having load profiles that vary by building type is especially important for the commercial buildings sector in which electric power usage patterns vary significantly. For example, the load profile for lighting technologies in warehouses is roughly constant for all 24 hours of the day, while that for small office space is high during workday hours and low overnight.

In the electric power module, GT-NEMS uses the lighting technologies selected by the commercial buildings sector to calculate the demand for electric power caused by lighting service. GT-NEMS' electric power module uses that quantity in its calculation of total electric demand for a given time period. The electric power module then calculates the least-cost means of generating electricity to meet that demand, including which power plants to operate, which fuels to burn for generation, and what kind of new power plant capacity to build. In calculating the optimal electricity generation strategy, GT-NEMS uses technology data from US DOE Energy Information Administration's Forms 860, 861, and 923; Federal Energy Regulatory Commission's Form 1; and North American Electric Reliability Corporation (NERC) projections (Smith & Brown, 2015). Users can represent alternative scenarios by manipulating, among other inputs, GT-NEMS' representation of greenhouse gas policies and technology options. Importantly, GT-NEMS' sector modules use different regional breakdowns. The commercial buildings module represents the United States through nine Census divisions, performing separate calculations of total energy demanded and technology portfolios selected for each Census division. Conversely, GT-NEMS' electric power module represents the United States through 22 regions partially based on regions designated by NERC.⁴³ Despite the difference between modules

⁴³ For a map, see https://www.eia.gov/analysis/requests/ces_hall/pdf/appc.pdf

in geographical representation, GT-NEMS accurately translates the energy consumption, prices, costs, and other calculations between the regional representations. GT-NEMS uses a conversion matrix based on historic energy consumption data to ensure that energy consumption calculated by census divisions is accurately apportioned among the electric power module's NERC-based regions.

5.4.1.1 Advantages to using GT-NEMS

For purposes of this study, GT-NEMS constitutes a superior choice to all alternatives for many reasons. The primary reason for choosing GT-NEMS over other options is that most energy modeling tools are not able to adequately represent both greenhouse gas policies for the electric power sector *and* end-use technologies like LED-based lighting technologies. GT-NEMS is the only nation-scale modeling tool capable of representing a portfolio of technology options for lighting service. GT-NEMS goes even farther in this particular advantage by addressing “rebound effects” of energy-efficient technologies, in a manner compatible with recent literature (Sorrell et al., 2009).⁴⁴ As such, GT-NEMS is also the only modeling tool capable of representing consumers' choice among competing technologies for lighting. Since we want to understand how greenhouse-gas policies and consumer technology choices interact, representing consumers' economic decision making of which lighting technology to use is critical for this study. GT-NEMS also offers a granular, large-scale, and computationally sophisticated representation of the electric power sector and its greenhouse gas emissions policies. Moreover, GT-NEMS represents

⁴⁴ Assumptions reflecting a stronger rebound effect might diminish some of the absolute magnitudes observed in this study, as the aggregate effect of such assumptions would be to decrease the absolute amount of energy saved by deployed LEDs. However, such assumptions would have general effects across all regions and building types and would therefore be unlikely to change the qualitative differences and other patterns of outcomes observed in the study.

interactions between the energy consumption sectors and the electric power sector's greenhouse gas emissions policies, making GT-NEMS perfectly suited to the needs of this study.

The superiority of GT-NEMS to alternatives becomes apparent when examining studies performed with other modeling tools. As described previously in the section on literature gaps, some studies have ignored energy efficiency entirely when examining options for mitigating the electric power sector's greenhouse gas emissions (Peters & Hertel, 2017). Other studies have taken crude and inadequate approaches to representing energy efficiency, such as assuming that energy demand is somehow mysteriously and exogenously reduced at some lump-sum cost to society. Many studies use such inadequate models and approaches, attempting to make sweeping statements about energy policy without considering granular realities, including examples such as: Integrated Planning Model (IPM) used by US Environmental Protection Agency (2014), MJ Bradley & Associates (2016), and the Bipartisan Policy Center (2016), the Haiku model used by Resources for the Future (Burtraw et al., 2016), US-REGEN used by the Electric Power Research Institute (2016), and FACETS-ELC used by Wright & Kanudia (2016)

Such approaches obviously fail to answer the question of how the reductions are achieved and what implications those reductions have for the portfolio of technologies used to consume energy by the residential and commercial sectors. Moreover, such modeling approaches cannot reflect instances when supply-side investments for meeting greenhouse

gas reduction requirements elevate electricity prices and make energy-efficient technologies, like LED-based lighting, more attractive to end-use consumers.⁴⁵

5.4.1.2 Controlling for rival hypotheses through GT-NEMS simulation designs

While experimental and quasi-experimental research designs must employ various techniques to eliminate rival hypothesis, the use of GT-NEMS simulation designs makes such techniques unnecessary by offering perfect control for rival hypotheses. Experimental and quasi-experimental research designs must contend with rival hypotheses, which are in essence alternative explanations of the data. These alternative explanations compete with the experimental or quasi-experimental researchers' main hypotheses by casting doubt on the belief that the researchers' findings truly reject or fail to reject the researchers' hypothesis. In plain language, as long as some explanation for the data remains a plausible alternative to the researchers' main explanation, ambiguity remains as to whether the research has truly tested the relevant theories. Given this circumstance, the experimental or quasi-experimental researcher must use elements of the research design to eliminate alternative explanations – in other words, to “control for” those rival hypotheses. Common examples include using laboratory conditions to hold constant elements of an environment other than the one being tested. Contrary to experimental and quasi-experimental research designs, however, the use of GT-NEMS to simulate responses of the US energy economy enables perfect control of rival hypotheses. GT-NEMS enables users with very precise control of rival hypotheses by allowing users to simulate scenarios with only one factor changed between them. All other conditions of the modeled US energy economy are held

⁴⁵ For further detail on the design and advantages of GT-NEMS, consult Brown et al. 2017.

constant. As such, any difference between the two simulated scenarios' results becomes entirely attributable to the single factor that was changed. No alternative explanations are plausible. The study's research design uses GT-NEMS to hold constant the influence of any other factor and to only change one factor at a time, and thus any other factors that might influence the outcomes of the study are controlled for.

5.4.2 Updating GT-NEMS to reflect the Clean Power Plan and contemporary policies

5.4.2.1 Representing the Clean Power Plan in GT-NEMS

This study uses several manipulations of input data and parameters to represent the Clean Power Plan in GT-NEMS. Because the Clean Power Plan defines the electric power sector's GHG reduction goals at the level of each US state, GT-NEMS uses a weighted aggregation to implement GHG reduction policies at the level of each of the electric power module's 22 regions. GT-NEMS uses data from 2012 on power-plant-level generation to weight the GHG reduction targets in the aggregation from state to region. The study implements each region's GHG policy as a cap on the upper limit of tons of CO₂ a region's electric power sector may emit in a given year. Moreover, the study scenarios apply the CO₂ limits to both existing and newly constructed power plants for the entire duration of the forecast period.

5.4.2.2 Updating the reference scenarios to reflect contemporary policies promoting wind and solar generation and to reflect the CPP's CEIP

In addition to modifying GT-NEMS' CO₂ emissions limits, this study makes several modifications to GT-NEMS' other input variables for purposes of representing certain

aspects of the Clean Power Plan as well as contemporary policies and latest data. The modifications follow those described in Brown et al. (2017), and the reader is directed to that source and its appendix for technical details. The modifications include:

- An update of cost data for distributed solar PV via review of contemporary estimates of distributed solar PV costs-per-kilowatt-dc
- An update of GT-NEMS' data reflecting the wind production tax credit, which was extended for five years via the US Congress' Consolidated Appropriations Act of 2015
- An update of GT-NEMS' data reflecting the solar investment tax credit, which was introduced via the US Congress' Consolidated Appropriations Act of 2015
- Further modifications making the wind production tax credit and the solar production tax credit more generous so as to reflect economic advantages granted to wind and solar resources under the Clean Power Plan's Clean Energy Incentive Program (CEIP)

5.4.2.3 Updating GT-NEMS to reflect advancements in LED technology and policies for promoting LEDs

To accurately represent SSL technology in NEMS, I update the model's representation of LED-based lighting technologies to reflect recent projections of product performance (Navigant Consulting, 2014). Good cause exists to deviate from GT-NEMS' default assumptions regarding projections of lighting technology performance and costs. Brown et al. (2017) used "High Tech" assumptions from the EIA's AEO 2015 to characterize lighting, in addition to several performance-enhancing assumptions to other technologies

(lighting and non-lighting) in tandem. Per EIA, however, the High Tech assumptions reflect a sensitivity scenario – a set of assumptions that have been deliberately biased in one direction or another to produce an expected directional change in a scenario’s outcomes. As such, the High Tech case assumptions aren’t strongly supported and aren’t intended to be – they exist simply to produce a scenario result that makes AEO 2015 readers aware of the potential consequences of unforeseen (and not necessarily rationalized) technological progress. As a sensitivity, therefore, the High-tech case cannot serve as a point of reference and cannot be useful in our hypothesis tests. Moreover, EIA appears to have used the DOE SSL program’s 2012 Multi-year Program Plan and 2012 Energy Savings Forecast Model as the source of assumptions for AEO 2015 Commercial LED technologies.⁴⁶ In doing so, EIA may have erroneously given LEDs greater efficiency than is reasonable. EIA applied luminaire efficiencies forecast in the 2012 MYPP to installed LED packages, which simply are not apples-to-apples equivalents of luminaires. Packages are always less efficient than luminaires, so EIA likely over-estimated the efficiency of LED technology in its AEO 2015 assumptions. From these observations, it is evident that more recent forecasts of LED product cost and performance are warranted - the defaults and the High Tech case assumptions from AEO 2015 are inadequate, may be erroneous, and don’t capture recent relevant information.

5.4.2.4 Updating GT-NEMS’ representation of Commercial Building LEDs

Referring to a Navigant Consulting (2014) study forecasting expected performance of LED lighting products, I make several updates to GT-NEMS’ representation of LED lighting

⁴⁶ US Energy Information Administration (April 2015) “Updated Buildings Sector Appliance and Equipment Costs.” Washington, USA: U.S Department of Energy. See pages 28 and 37.

products in the commercial sector. I make some of the modifications to a single file through which GT-NEMS represents all energy-consuming technologies for the commercial demand sector, a file called “KTEK.” The KTEK file identifies each technology via a “t” value, representing the technology type; and a “v” value, representing the vintage of the technology. This arrangement allows KTEK to represent future improved versions of a technology as new vintages that first become available in future years, such as a highly-efficient LED product becoming available in 2025. KTEK uses a set of other parameters, including cost-per-unit of light provided, year of entry into the marketplace, year of exit from the marketplace, and useful life to represent each technology. Table 14 below describes my modifications to KTEK, including the justification for each modification made.

Table 14: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector

| t | v | Technology name | Edits | Grounds |
|----|----|--------------------------------|---|---|
| 24 | 26 | LED Edison 2007 installed base | new y2: 2013 | this product should phase out sooner to reflect improvement in overall LED product portfolio |
| 24 | 27 | LED Edison 2011 typical | new technology names = LED Edison 2013 typical; new y2: 2020; new eff: 59.6; new c1: 115.27 | The expected cost of a LED A-lamp in 2013 is \$115.27/k-lm according to Navigant projections. The expected efficacy of a LED A-lamp in 2013 is 59.6 lm/W according to Navigant projections. This product should phase out sooner to reflect improvement in overall LED product portfolio. |
| 24 | 28 | LED Edison 2020 typical | new y2: 2030; new eff: 88.15; new c1: 61.31; new c4 (Subsidy_111d_cost): 0 | The expected cost of a LED A-lamp in 2020 is \$61.31/k-lm according to Navigant projections. The expected efficacy of a LED A-lamp in 2020 is 88.15 lm/W according to Navigant projections. Our default scenario will have no subsidies to the technologies. |

Table 15, continued: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector

| | | | | |
|----|----|--------------------------------|--|--|
| 24 | 29 | LED Edison 2030 typical | new technology name = LED Edison 2025 typical; new y1: 2023; new y2: 2030; new eff: 102.9; new c1: 42.12; new c4 (Subsidy_111d_cost): 0 | The expected cost of a LED A-lamp in 2025 is \$42.12/k-lm according to Navigant projections. The expected efficacy of a LED A-lamp in 2025 is 102.9 lm/W according to Navigant projections. Our default scenario will have no subsidies to the technologies |
| 24 | 30 | LED Edison 2011 typical (111d) | new technology name = LED Edison 2030 typical; new y1: 2030; new y2: 2040; new eff: 114.98; new c1: 30.99; new c4 (Subsidy_111d_cost): 0 | The expected cost of a LED A-lamp in 2025 is \$30.99/k-lm according to Navigant projections. The expected efficacy of a LED A-lamp in 2025 is 114.98 lm/W according to Navigant projections. Our default scenario will have no subsidies to the technologies. We need a new late-stage technology (>2030). |
| 25 | 24 | LED T8 2011 typical | new technology name = LED T8 2013 typical; new y2: 2020; new eff: 167.66; new c1: 85.64 | The expected cost of a LED troffer in 2013 is \$85.64/k-lm according to Navigant projections. The expected efficacy of a LED troffer in 2013 is 167.66 lm/W according to Navigant projections. |
| 25 | 27 | LED T8 2011 typical (111d) | new technology name = LED T8 2017; new y2: 2023; new eff: 119.1; new c1: 59.89; new c4 (subsidy_111d_cost): 0 | The expected cost of a LED troffer in 2013 is \$59.89/k-lm according to Navigant projections. The expected efficacy of a LED troffer in 2013 is 119.1 lm/W according to Navigant projections. Our default scenario will have no subsidies to the technologies |
| 25 | 25 | LED T8 2020 typical | new technology name = LED T8 2023 typical; new y1: 2023; new y2: 2030; new eff: 142.4; new c1: 36.01; ; ; ; | The expected cost of a LED troffer in 2013 is \$36.01/k-lm according to Navigant projections. The expected efficacy of a LED troffer in 2013 is 142.4 lm/W according to Navigant projections. Our default scenario will have no subsidies to the technologies |
| 25 | 26 | LED T8 2030 typical | new eff: 167.67; new c1: 23.02 | The expected cost of a LED troffer in 2013 is \$23.02/k-lm according to Navigant projections. The expected efficacy of a LED troffer in 2013 is 167.67 lm/W according to Navigant projections. |

Table 16, continued: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector

| | | | | |
|----|----|---|--|--|
| 25 | 14 | LED T8 2011 typical | changed this vintage to match changed v=24 for the same technology | for some reason the default KTEK file has two product specifications, t=25:v=27; and t=26:v=14, with the same parameters. Don't need duplicate LED techs with less-accurate parameters |
| 25 | 17 | LED T8 2011 typical (111d) | changed this vintage to match changed v=27 for the same technology | don't need duplicate LED techs with less-accurate parameters |
| 25 | 15 | LED T8 2020 typical | changed this vintage to match changed v=25 for the same technology | don't need duplicate LED techs with less-accurate parameters |
| 25 | 16 | LED T8 2030 typical | changed this vintage to match changed v=26 for the same technology | don't need duplicate LED techs with less-accurate parameters |
| 27 | 17 | LED 100 HPS_LB 2011 typical | new technology name = LED 100 HPS_LB 2013 typical; new eff = 82.6; new c1 = 84.80 | 2013 value for efficacy (lm/W) of roadway and parking area lamps is 82.6 using PNNL formulae; 2013 value for cost of (\$/k-lm) roadway and parking area lamps is 82.6 using PNNL formulae; Changed name to reflect that the data I used here come from the 2013 values from the PP |
| 27 | 20 | LED 100 HPS_LB 2011 typical (111d) | new y2 = 2025; new technology name = LED 100 HPS_LB 2020 typical; new eff = 114.11; new c1 = 45.11; new c4 = 0 | 2020 value for efficacy (lm/W) of roadway and parking area lamps is 114.11 using PNNL formulae; 2020 value for cost of (\$/k-lm) roadway and parking area lamps is 45.11 using PNNL formulae; Changed name to reflect that the data I used here come from the 2020 values from the PP; No 111d subsidies in my default case |
| 27 | 18 | LED 100 HPS_LB 2020 typical | new y1 = 2025; new y2 = 2035; new technology name = LED 100 HPS_LB 2025 typical; new eff = 130.41; new c1 = 30.99; new c4 = 0; ; ; | 2020 value for efficacy (lm/W) of roadway and parking area lamps is 114.11 using; PNNL formulae; 2020 value for cost of (\$/k-lm) roadway and parking area lamps is 45.11 using; PNNL formulae; Changed name to reflect that the data I used here come from the 2025 values from; the PP; No subsidies in my default case; ; |

Table 17, continued: List of modifications to KTEK file to represent recent expectations regarding performance improvements for LED lighting products in the commercial sector

| | | | | |
|----|----|------------------------------------|--|--|
| 27 | 19 | LED 100 HPS_LB 2030 typical | new technology name = LED 100 HPS_LB 2025 typical; new eff = 141.25; new c1 = 22.80; new c4 = 0; ; ; ; ; | 2030 value for efficacy (lm/W) of roadway and parking area lamps is 141.25 using; PNNL formulae; 2030 value for cost of (\$/k-lm) roadway and parking area lamps is 22.80 using; PNNL formulae; No subsidies in my default case; ; ; |
| 28 | 20 | LED 150 HPS_HB 2011 typical | new technology name = LED 150 HPS_HB 2013 typical; new eff = 82.63; new c1 = 48.29; new c4 = 0; ; ; ; ; | 2013 value for efficacy (lm/W) of roadway and parking area lamps is 82.63 using; PNNL formulae; 2013 value for cost of (\$/k-lm) roadway and parking area lamps is 48.29 using; ; PNNL formulae; changed the name to reflect that I'm using the 2013 data; ; |
| 28 | 21 | LED 150 HPS_HB 2020 typical | new eff = 114.11; new c1 = 25.68; new c4 = 0 | 2020 value for efficacy (lm/W) of roadway and parking area lamps is 114.11 using PNNL formulae; 2020 value for cost of (\$/k-lm) roadway and parking area lamps is 25.68 using PNNL formulae; no subsidies in my default case |
| 28 | 22 | LED 150 HPS_HB 2030 typical | new technology name = LED 150 HPS_HB 2025 typical; new eff = 130.41; new c1 = 17.64; new c4 = 0; new y1 = 2025; new y2 = 2035; ; ; | 2025 value for efficacy (lm/W) of roadway and parking area lamps is 130.41 using PNNL formulae; 2035 value for cost of (\$/k-lm) roadway and parking area lamps is 17.64 using PNNL formulae |
| 28 | 23 | LED 150 HPS_HB 2011 typical (111d) | new technology name = LED 150 HPS_HB 2030 typical; new eff = 143.73; new c1 = 12.98; new c4 = 0; new y1 = 2030; new y2 = 2052 | 2030 value for efficacy (lm/W) of roadway and parking area lamps is 143.73 using PNNL formulae; 2030 value for cost of (\$/k-lm) roadway and parking area lamps is 12.98 using PNNL formulae |

Note: This table's changes apply to all regions, i.e. all values of "r", and apply to service-demand type 6 (lighting), and to "f" type 1 (electricity)

5.4.2.5 LEDs for Roadways and Parking Structures

GT-NEMS requires special modifications made to the commercial sector module for modeling energy savings in roadway and parking lighting technologies. GT-NEMS calculates the amount of energy consumption for roadway and parking lighting through a combined use of SEDS data, CBECS data, and the growth rate of floorspace in the commercial sector. First, GT-NEMS calculates the difference in energy consumption for each census region between the latest Annual Energy Review (AER)'s commercial-sector energy consumption and NEMS' internal calculation of historic energy consumption based upon the Commercial Buildings Energy Consumption Survey (CBECS). GT-NEMS labels the difference between the AER amount and the CBECS-based calculation as the "mistie." Because the AER summarizes historic energy consumption for the entire commercial sector while the CBECS-based calculation reflects only buildings-driven energy consumption, the mistie represents commercial sector energy consumption not occurring in buildings – such as energy consumption by lighting for roadways and parking areas. After calculating the initial AER-CBECS mistie, NEMS then calculates the annual non-building energy consumption by increasing the amount of the mistie in each census region in proportion to the growth rate for commercial floorspace for the census region in the forecast year of interest. NEMS therefore embodies an assumption that energy consumption for roadway and parking area lighting grows at the same rate as commercial building floorspace.

The research documented here models growth of the SSL technology market share growth in roadway and parking area lighting to 100% by 2030 - that is, the research models a scenario in which all roadway and parking area lighting is delivered by SSL technologies. Prior work supports the focus on a 100% roadway and parking area lighting market share

scenario (Navigant Consulting, 2014). In particular, prior work by Navigant calculates exact amounts of lighting energy savings under a complete conversion of roadway and parking area lighting to SSL technologies. Table 3.7 and Table 3.8 in the Navigant report display the energy savings estimated for roadway lighting and parking lighting, respectively – a cumulative total of 137 TWh for roadway lighting during 2013-2030 and 172 TWh for parking lighting during 2013-2030.

The research implements the savings in energy consumption for parking and roadway lighting by subtracting the energy savings amounts estimated in the Navigant report from the total non-building energy consumption estimated by NEMS in each year. The research uses linear interpolation to estimate energy savings for years not reported in Table 3.7 and Table 3.8. I subtract the sum total of annual energy savings for roadway lighting and for parking lighting from NEMS' estimated non-building energy consumption in each year to yield estimates of non-building energy consumption that account for a 100% conversion to SSL technology for roadway and parking lighting.

Subtracting the roadway and parking lighting energy savings from non-building energy consumption requires modifying the CDM source code. NEMS' estimated non-building energy consumption is stored in a variable called "CMNonBldgUse", which is indexed by fuel type, census division, and year. Lines 8477-8509 provide the final calculation of non-building electricity consumption – CMNonBldgUse for fuel 1, electricity. While many of the lines are dedicated to modeling compliance with the traffic signal standards created by the 2005 Energy Policy Act (109th Congress, 2005), the code lines 8502-8506 are dedicated to calculating CMNonBldgUse for electricity for years after 2015. As such, I subtract the energy savings for the census division and year of interest from the

calculation of CMNonBldgUse for electricity that begins on line 8502. To reflect the savings from 100% conversion of roadway and parking lighting to SSL technologies, I first create an array in the source code that stores the lighting energy savings values from the Navigant report; the array is indexed by year and census division to reflect the structure of the CMNonBldgUse variable and to reflect that the savings apply only to electricity. I then modify lines 8506 and 8507 of the CDM source code to subtract the value of the array from the CMNonBldgUse variable for each combination of fuel, year, and census division. Making use of the Navigant forecast of energy savings in roadway and parking lighting requires apportioning national totals to the 9 census divisions; to apportion the energy savings, I divide the national energy savings by the percentage of total electricity consumed by the commercial sector nationwide made up by each census divisions' commercial sector. That is, I calculate the energy savings for each census division as

$$\text{CensusLightingEnergySavings_yr} = \text{NationalLightingEnergySavings_yr} * (\text{CensusCommercialElectricityConsumption_yr} / \text{NationalCommercialElectricityConsumption_yr}).$$

While the array of national roadway and parking energy savings is indexed by fuel type, the only non-zero values in the array are for the electricity fuel ($f = 1$) as lighting energy savings forecast by Navigant apply only to electricity. I name the array "RoadParkSave," and I declare the array of lighting savings with the FORTRAN statement:

INTEGER*3 RoadParkSave(MNUMCR-2,MNUMYR)

Where “MNUMCR” refers to the maximum number of regions used by the CDM and “MNUMYR” refers to the maximum number of years in the NEMS forecast. The maximum number of regions in the CDM is 11, even though there are only 9 census division, because the CDM uses region 10 to represent California and region 11 to represent the US. The CDM represents California in addition to using region 9 to represent the Pacific Northwest census division for the purposes of implementing commercial sector energy regulations that are passed only in California. I program values into the RoadParkSave array in the units of trillion Btus, since the CMNonBldgUse variable is declared in units of trillion Btus.

The calculations that apportion national roadway and parking lighting energy savings use commercial sector consumption of delivered electricity in 2012 as the basis for apportionment. Delivered electricity excludes the amount of energy lost through transmission lines and the amount of primary energy lost via inefficiencies of power plants; instead, delivered electricity refers only to the electricity that was made available to the consumer to perform useful work. Table 2, Row 25 of the NEMS output in GRAF2000 supplies the quantities used for the apportionment calculation. I chose to use the 2012 commercial sector consumption of delivered electricity to implement an assumed proportionality between commercial sector electricity-consuming activity and non-building electricity consumption.

To match the year indexing of the CMNonBldgUse variable, the array of energy savings values for roadway and parking lighting is indexed by year from 2004 to 2040. According

to the NEMS Restart GAMS file, restart.GDX, the COMMREP_CMNonBldgUse variable (representing the CMNonBldgUse variable in the CDM) is indexed by MNUMYR and goes from 2004 to 2040. The indexing of CMNonBldgUse. To view the indexing of the CMNonBldgUse variable, I first unzip the restart.gdx.gz file in the NEMS run output directory and then use the GAMS IDE on the NEMS server to open the resulting restart.gdx file. COMMREP_CMNonBldgUse resides under the “symbol” heading. See directions under the file “Interactive_access_to_the_NEMS_restart_file_as_gdx.doc” in the “*Doc/” folder of the NEMS distribution. The CMNonBldgUse variable is indexed by the 9 census divisions and for the US as whole (region 11).

5.4.2.6 Defining analysis regions by pairing Census Divisions with electric power regions

To address the research question and test hypotheses posited earlier, the analysis defines four regions as units of analysis between which outcomes can be compared. Because the GT-NEMS model implements two distinct topographies of regions for energy consumption and electric power supply, the four regions used in this analysis comprise pairings of regions from each topography. For energy consumption, the GT-NEMS model uses nine Census Divisions to divide the continental US. Conversely, the GT-NEMS model represents electric power supply delivery uses a set of regions based loosely on the North American Electric Reliability Council (NERC)’s Regional Entity regions. Given the two distinct topographies, choosing pairings that are geographically coincident or economically interrelated becomes necessary when comparing GT-NEMS’ regional calculations across the consumption and supply sectors. This analysis forms regions for units of analysis by making the following pairings within GT-NEMS’ consumption and supply topographies. The analysis pairs GT-NEMS’ electric power region "CAMX" with the ninth Census

Division, “Pacific,” on the grounds that CAMX largely represents California’s power sector and, because California is a major importer of electric power from the rest of the pacific division, the entire pacific division's LED adoption will arguably influence the CAMX region’s power sector outcomes. GT-NEMS’ electric power region "NEWE" matches the same exact geographic territory as the first Census Division, “New England.” Four of GT-NEMS’ power supply regions – NYU, PNYCW, NYLI, and RFCE – accurately represent the supply serving major load centers in the Middle Atlantic Census Division, so these four supply regions are paired with the Middle Atlantic Census Division. Finally, three of GT-NEMS’ electric power supply regions – SPSO, TRE/ERCT, and SRDA –represent supply serving load centers in the West South Central census division, and also largely share the same geographic territory – as such, these three supply regions are paired with the West South Central Census Division. Taken together, the regions formed for this analysis are summarized in Table 17.

Table 18: Table of paired census divisions with NEMS EMM regions for analysis

| Census Division | EMM Region |
|---|------------------------|
| 20 – Western Electricity Coordinating Council / California, i.e. CAMX | 9 – Pacific |
| 05 – Northeast Power Coordinating Council / New England | 1 – New England |
| 06 – Northeast Power Coordinating Council / NYC-Westchester 07 – Northeast Power Coordinating Council / Long Island 08 – Northeast Power Coordinating Council / Upstate New York 09 – Reliability First Corporation / East | 2 – Middle Atlantic |
| 1 – Texas Regional Entity 12 – SERC Reliability Corporation / Delta 18 – Southwest Power Pool / South | 7 – West South Central |

5.4.3 Scenario nomenclature

For ease-of-reading, I have created shorthand names for all scenarios simulated in this study. Table 18 lists each scenario with its shorthand name and a description of its key features.

Table 19: List of Scenario names with descriptions of each

| Scenario Name | Shorthand | Scenario Description |
|---------------|-----------|--|
| CPP_AllRS | | CPP_AllR, plus updates to the RSMLGT and KTEK files to reflect recent expectations regarding LED lighting technology performance |
| CPP_AllRSG | | CPP_AllRS, plus a 15% government subsidy for LED lighting technologies |

5.5 Results from methodology

This section presents the results of using GT-NEMS to analyze LED adoption and power sector outcomes. The section first presents demand-side results, i.e. results reflecting LED adoption among the four regions inspected. Each region's results are given and a final sub-section compares results between regions. Then, the section presents supply-side results, i.e. results reflecting impacts of LED adoption on the power sector outcomes. Again, each region's results are presented in a separate sub-section, and a final sub-section offers comparisons across regions.

5.5.1 Demand-side results: LED adoption nationally and among four census divisions

This section presents the modeled adoption of LED products among the four census divisions of interest. The results are organized by division; charts and tables appear

alongside description of each, and the end of this section presents comparisons and interpretations. The LED adoption levels are measured as “service demand” met by LEDs which is the amount of demand for lighting met by LED technologies. The adoption levels are stratified by eleven building types and three decision types. The eleven building types represent functional categories of building floor space and provide insight as to the types of buildings into which LEDs are modeled to be installed.

5.5.1.1 1 - New England

Table 19 compares the LED adoption levels within the New England region under the CPP_AllRS scenario to those of the CPP_AllRSG scenario. Minimal gains occur under the subsidy case in 2020, but by 2040 the subsidy case shows over 20% more service demand met by LEDs. Under the CPP+subsidy case, growth in service demand met by LEDs follows a gradual pattern similar to that of the CPP-only case.

Table 20: Service Demand met by LEDs in New England under the CPP+Subsidy and CPP-only cases

| | 2020 | 2030 | 2040 |
|---------------------------------------|------|------|------|
| SD met by LED: CPP_AllRS (MMBtu-out) | 2 | 17 | 46 |
| SD met by LED: CPP_AllRSG (MMBtu-out) | 3 | 20 | 56 |
| Increase under CPP_AllRSG (MMBtu-out) | 0 | 3 | 10 |
| Percentage Increase (%) | 13% | 15% | 22% |

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-AllRSG scenario, Figure 26 displays the share of the total increase attributed to each building type. For New England, LEDs installed in 10 (Warehouses), 6 (Lodging), and 5

(Healthcare) dominate the early growth in service demand met by LEDs, while late growth is dominated by 11 (Other), 9 (Mercantile & Service), and 7 (Large Office). Intermediate growth is dominated by 9 (Mercantile and Service).

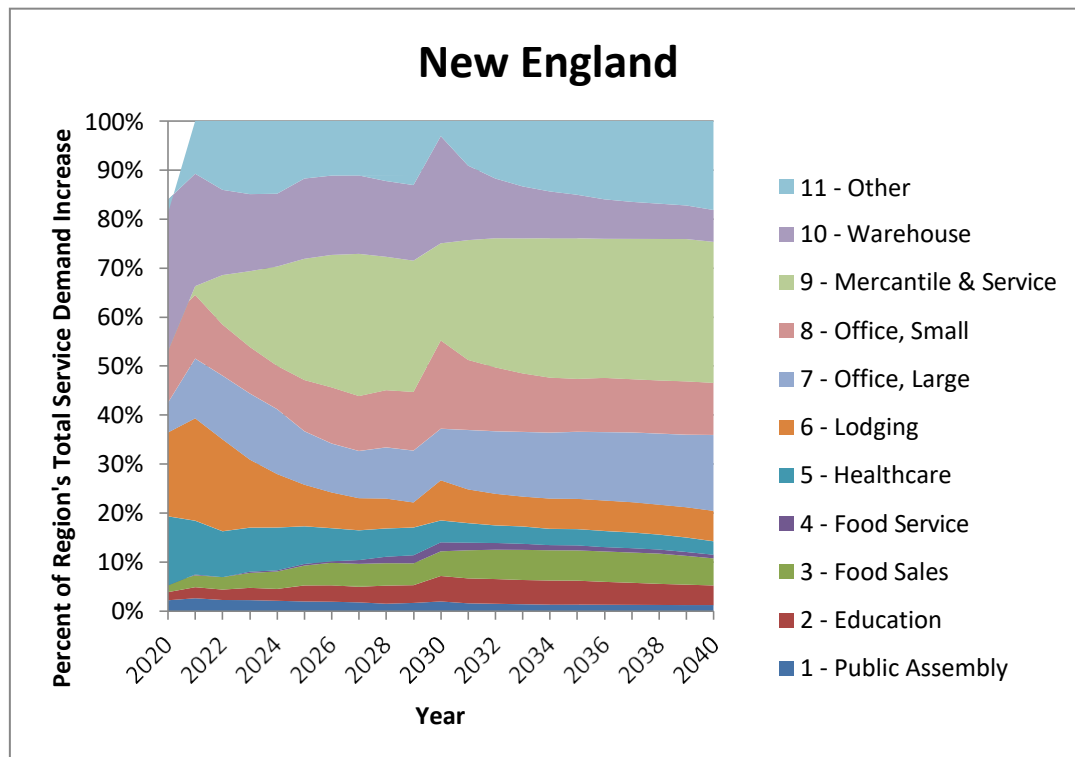


Figure 26: For New England, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-ALLRSG scenario, Figure 27 displays the absolute amount of increase attributed to each building type for select years of 2020, 2030, and 2040. Trends in absolute LED growth by building type largely follow trends observed in shares of total LED growth attributable to

each building type, with 11 (Other), 9 (Mercantile & Service), and 7 (Large Office) exhibiting the greatest late-term LED growth.

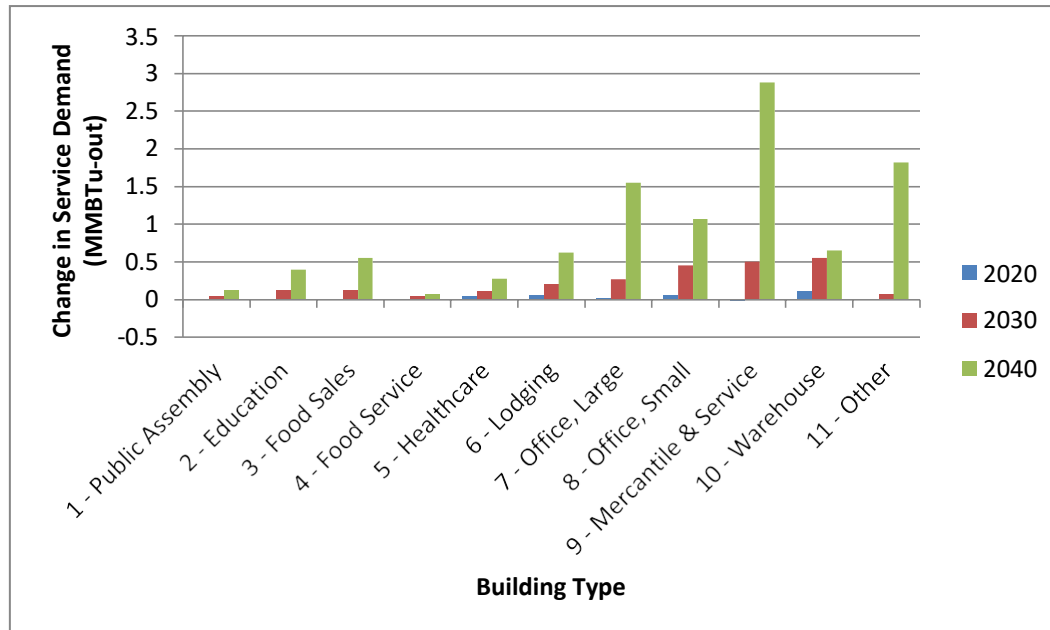


Figure 27: Absolute amount of LED increase attributed to each building type for select years

5.5.1.2 2 – Middle Atlantic

Table 20 compares the LED adoption levels within the Middle Atlantic region under the CPP_AllRS scenario to those of the CPP_AllRSG scenario. Minimal gains occur under the subsidy case in 2020, but by 2040 the subsidy case shows 20% more service demand met by LEDs. Under the CPP+subsidy case, growth in service demand met by LEDs follows a gradual pattern similar to that of the CPP-only case.

Table 21: Service Demand met by LEDs in Mid Atlantic under the CPP+Subsidy and CPP-only cases

| | 2020 | 2030 | 2040 |
|---------------------------------------|------|------|------|
| SD met by LED: CPP_AllRS (MMBtu-out) | 5 | 50 | 148 |
| SD met by LED: CPP_AllRSG (MMBtu-out) | 6 | 58 | 177 |
| Increase under CPP_AllRSG (MMBtu-out) | 0 | 8 | 30 |
| Percentage Increase (%) | 9% | 16% | 20% |

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-AllRSG scenario, Figure 28 displays the share of the total increase attributed to each building type. For Mid-Atlantic, LEDs installed in 9 (Mercantile & Service), 8 (Small Office), and 4 (Food Service) dominate the early growth in service demand met by LEDs, while late growth is dominated by 7 (Large Office), 9 (Mercantile & Service), and 11 (Other). Intermediate growth is dominated by 10 (Warehouse).

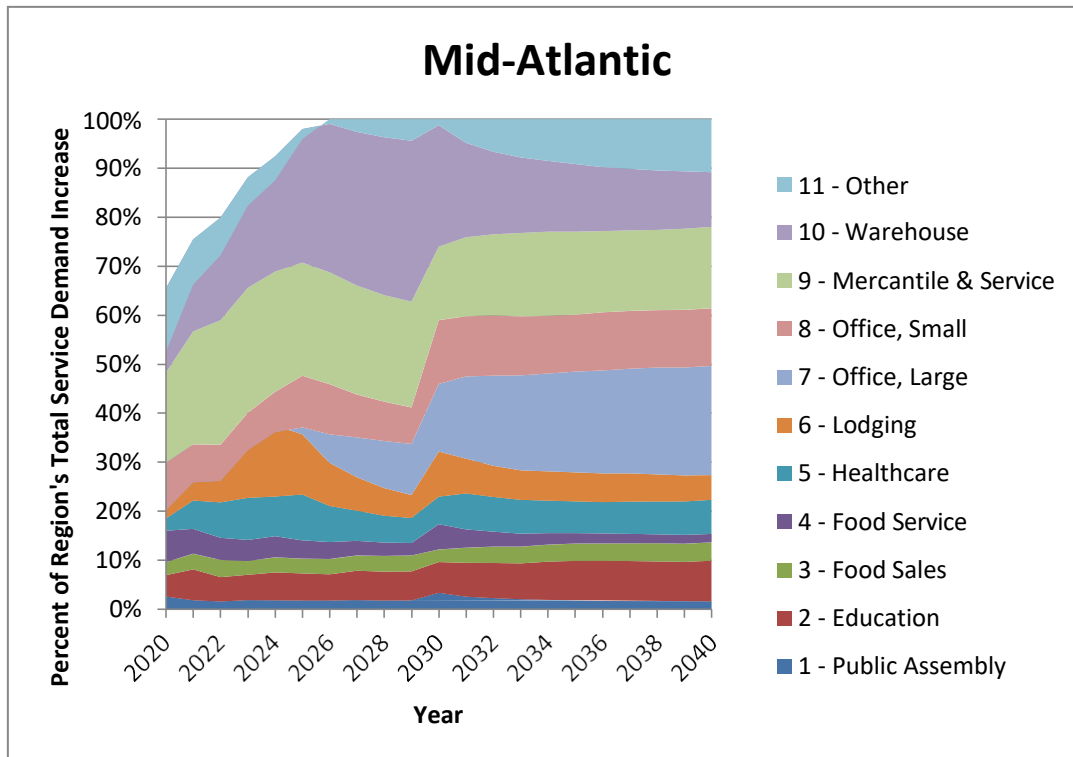


Figure 28: For Mid-Atlantic, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-ALLRSG scenario, Figure 29 displays the absolute amount of increase attributed to each building type for select years of 2020, 2030, and 2040. Trends in absolute LED growth by building type largely follow trends observed in shares of total LED growth attributable to each building type, with 7 (Large Office), 9 (Mercantile & Service), and 8 (Small Office) exhibiting the greatest late-term LED growth. Worth noting is that 11 (Other) constitutes a slightly larger share of total late-term LED growth than 8 (Small Office), but 8 (Small Office) exhibits slightly larger absolute late-term LED growth; the two building types exhibit similar late-term LED growth overall, however.

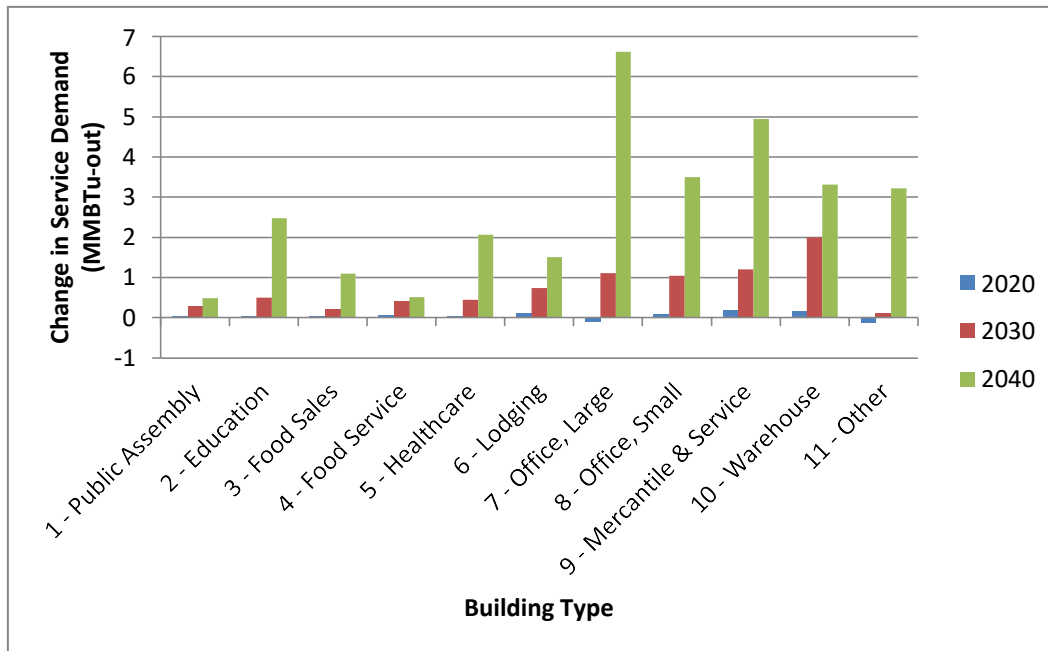


Figure 29: Absolute amount of LED increase attributed to each building type for select years

5.5.1.3 7 – West South Central

Table 21 compares the LED adoption levels within the West South Central region under the CPP_AllRS scenario to those of the CPP_AllRSG scenario. Minimal gains occur under the subsidy case in 2020, but by 2040 the subsidy case shows over 20% more service demand met by LEDs. Under the CPP+subsidy case, growth in service demand met by LEDs follows a gradual pattern similar to that of the CPP-only case.

Table 22: Service Demand met by LEDs in West South Central under the CPP+Subsidy and CPP-only cases

| | 2020 | 2030 | 2040 |
|---------------------------------------|------|------|------|
| SD met by LED: CPP_AllRS (MMBtu-out) | 5 | 51 | 158 |
| SD met by LED: CPP_AllRSG (MMBtu-out) | 5 | 59 | 192 |
| Increase under CPP_AllRSG (MMBtu-out) | 1 | 7 | 31 |
| Percentage Increase (%) | 10% | 16% | 22% |

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-AllRSG scenario, Figure 30 displays the share of the total increase attributed to each building type. For West South Central, LEDs installed in 8 (Small Office), 4 (Food Service), and 3 (Food Sales) dominate the early growth in service demand met by LEDs, while late growth is dominated by 9 (Mercantile & Service), 7 (Large Office), and 8 (Small Office). Intermediate growth is dominated by 9 (Mercantile & Service).

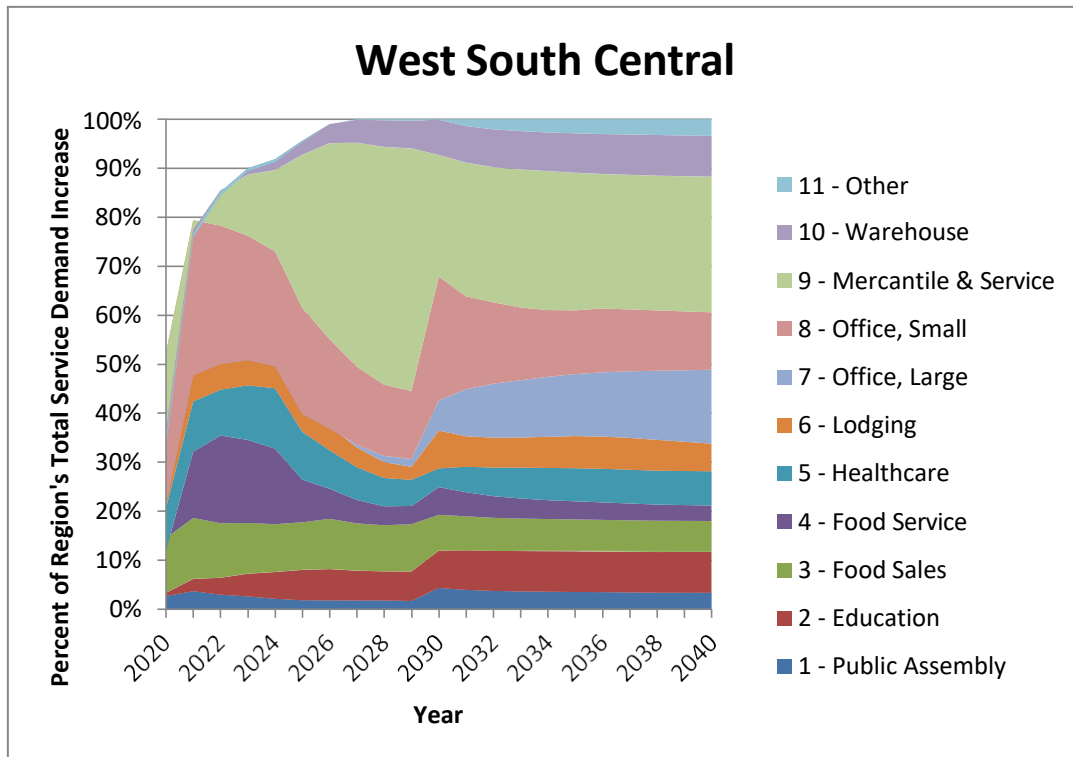


Figure 30: For West South Central, percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-ALLRSG scenario, Figure 31 displays the absolute amount of increase attributed to each building type for select years of 2020, 2030, and 2040. Trends in absolute LED growth by building type largely follow trends observed in shares of total LED growth attributable to each building type, with 7 (Large Office), 9 (Mercantile & Service), and 8 (Small Office) exhibiting the greatest absolute late-term LED growth.

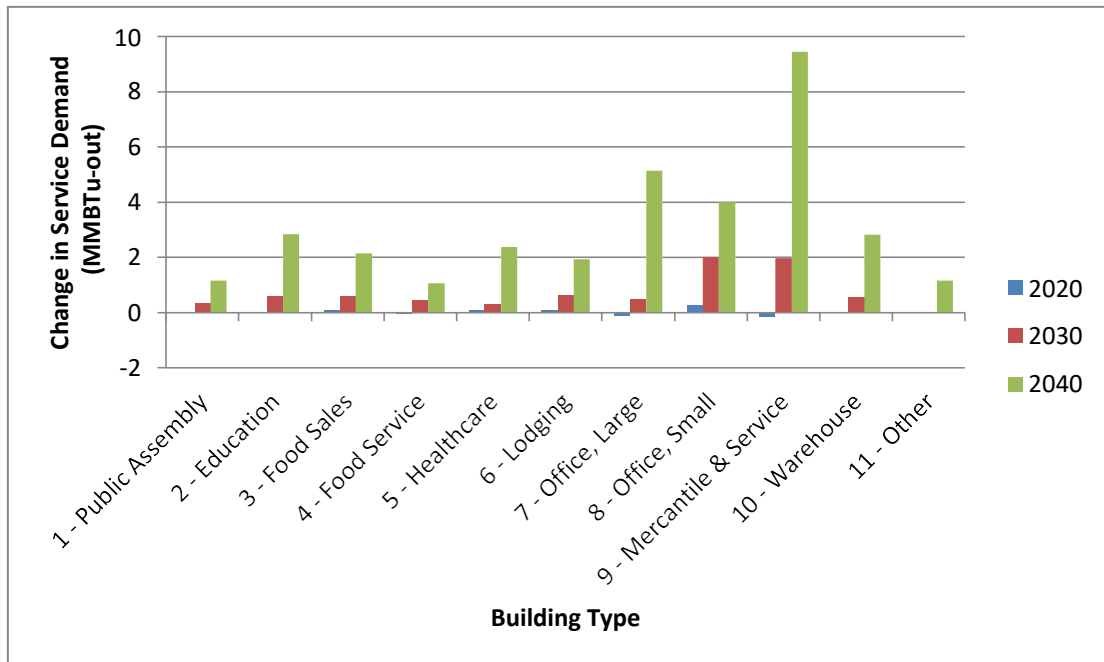


Figure 31: Absolute amount of LED increase attributed to each building type for select years

5.5.1.4 9 – Pacific

Table 22 compares the LED adoption levels within the Pacific region under the CPP_AllRS scenario to those of the CPP_AllRSG scenario. Minimal gains occur under the subsidy case in 2020, but by 2040 the subsidy case shows over 20% more service demand met by LEDs. Under the CPP+subsidy case, growth in service demand met by LEDs follows a gradual pattern similar to that of the CPP-only case.

Table 23: Service Demand met by LEDs in Pacific region under the CPP+Subsidy and CPP-only cases

| | 2020 | 2030 | 2040 |
|---------------------------------------|------|------|------|
| SD met by LED: CPP_AllRS (MMBtu-out) | 5 | 46 | 142 |
| SD met by LED: CPP_AllRSG (MMBtu-out) | 6 | 53 | 173 |
| Increase under CPP_AllRSG (MMBtu-out) | 1 | 7 | 31 |
| Percentage Increase (%) | 10% | 16% | 22% |

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-AllRSG scenario, Figure 32 displays the share of the total increase attributed to each building type. For Pacific, LEDs installed in 9 (Mercantile & Service), 8 (Small Office), and 5 (Healthcare) dominate the early growth in service demand met by LEDs, while late growth is dominated by 9 (Mercantile & Service), 8 (Small Office), and 7 (Large Office). Intermediate growth is dominated by 9 (Mercantile & Service).

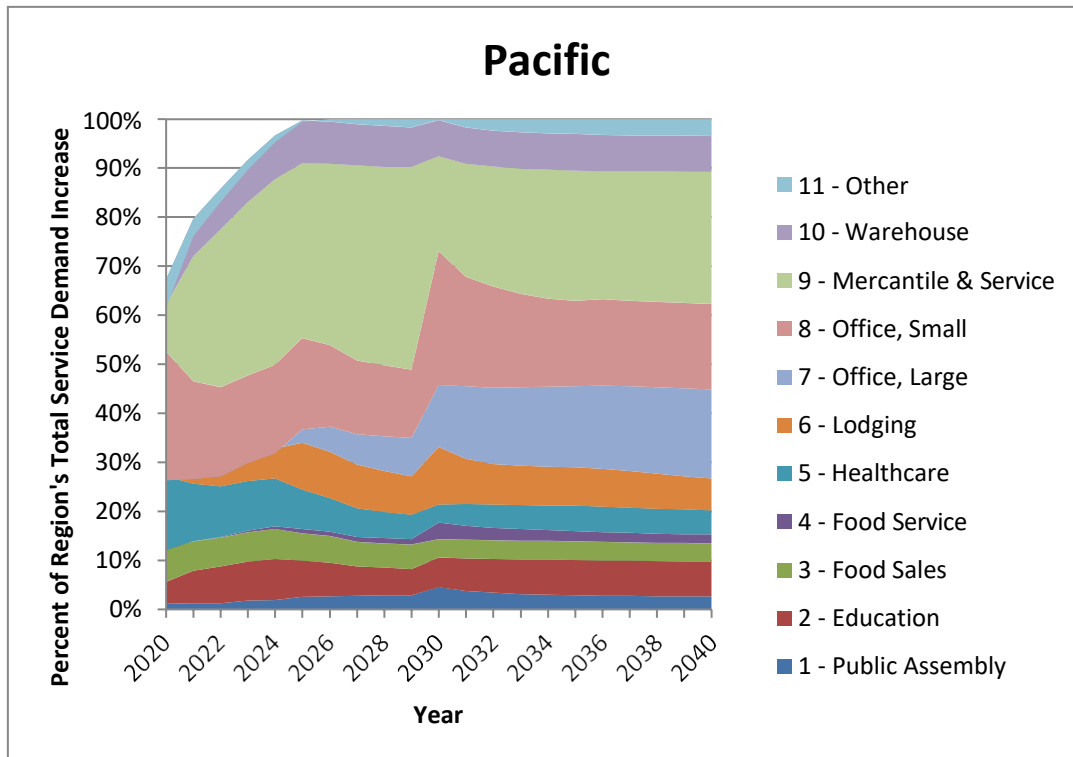


Figure 32: For Pacific, percent of the total increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types

For increases relative to the CPP-ALLRS scenario in LED adoption observed in the CPP-ALLRSG scenario, Figure 33 displays the absolute amount of increase attributed to each building type for select years of 2020, 2030, and 2040. Trends in absolute LED growth by building type largely follow trends observed in shares of total LED growth attributable to each building type, with 7 (Large Office), 9 (Mercantile & Service), and 8 (Small Office) exhibiting the greatest absolute late-term LED growth.

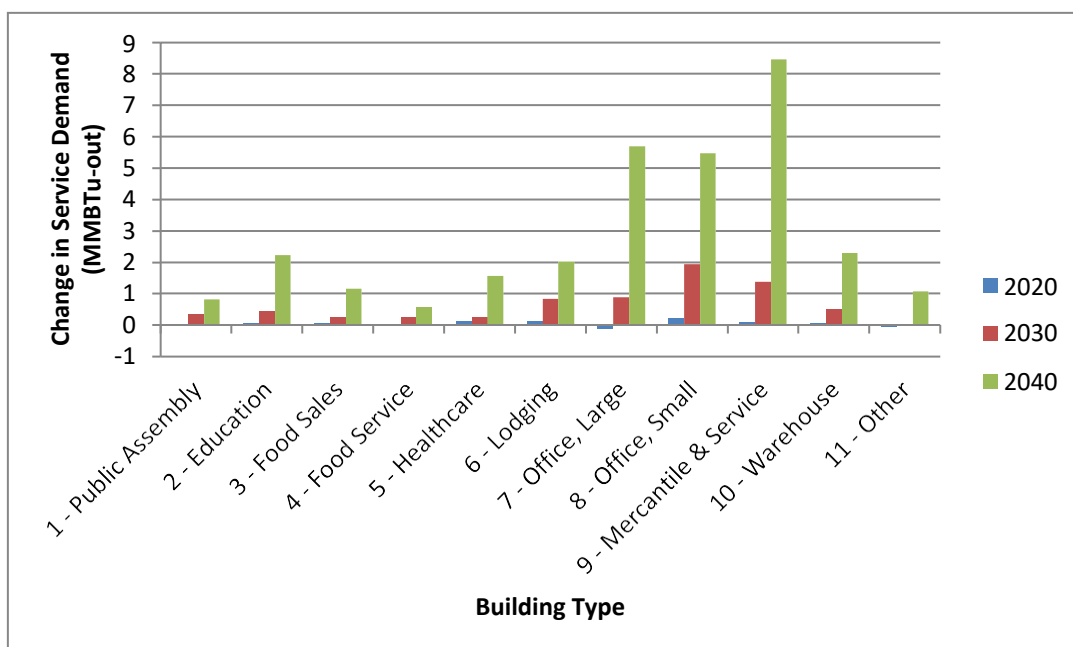


Figure 33: Absolute amount of LED increase attributed to each building type for select years

5.5.1.5 Comparisons: LED adoption

Comparing results from the four regions reveals several interesting findings regarding LED adoption within commercial buildings. Across all four regions, building types that are major lighting users do not feature as dominant LED adopters when exposed to a subsidy, while less-lighting-intensive building types exhibit the largest LED adoption. Unique to the Mid-Atlantic, warehouses come to dominate LED adoption in late 2020s and early 2030s, but in no other region or time period do warehouses feature as strong LED adopters. And finally, commercial buildings of type “Other” exhibit strong late-term LED adoption in New England and Mid-Atlantic regions but unremarkable LED adoption in the West South Central and Pacific regions.

Across all four regions, building types that are major lighting users do not feature as dominant LED adopters when exposed to a subsidy, contradicting the hypothesis that subsidy-driven LED growth among building types would be proportionate to lighting service usage. Education buildings, despite being the third most intensive user of lighting service according to EIA data,⁴⁷ do not account for much growth in any of the regions or in any timeframe of the forecast. Healthcare buildings, the second most intensive user of lighting services, only constitutes a large portion of subsidy-driven LED growth in the New England and Pacific regions during the early term of the forecast, and in no other region or timeframe. Finally, Food Sales buildings – the most intensive lighting services user of all – constitute a major portion of subsidy-driven LED growth *only* during the early period of the forecast for the West South Central region. These results suggest that lighting usage alone does not drive the cost-savings benefits that motivate subsidy-driven LED adoption.

By contrast, across all regions and for many periods of the forecast, building types of intermediary lighting intensity make up the largest share of subsidy-driven growth in LED adoption, further contradicting the hypothesis that subsidy-driven LED growth among building types would be proportionate to lighting service usage. Mercantile & Service buildings feature most frequently as dominant LED adopters across multiple time periods for all four regions. Moreover, Small Office buildings and Large Office buildings frequently dominate subsidy-driven LED growth in the intermediate and late time periods. This result contrasts the ranking of Mercantile & Service, Small Office, and Large Office buildings in terms of lighting usage - Mercantile & Service and Office (Large and Small)

⁴⁷ See “Top light-consuming building types” section above discussing EIA data on lighting consumption in commercial buildings.

building types are 4th and 5th most intensive users of lighting, respectively. These results add weight to the counterintuitive idea that lighting usage alone does not drive the cost-savings benefits that motivate subsidy-driven LED adoption.

As a surprising finding, commercial buildings of the very diverse type “Other” exhibit strong late-term LED adoption in New England and Mid-Atlantic regions but unremarkable LED adoption in the West South Central and Pacific regions. “Other”-type buildings come from a wide variety of functional categories that include both “Other”-typed buildings from the EIA’s Commercial Building Energy Consumption Survey (CBECS) and a few categories added on by EIA’s NEMS development group. The CBECS definition of “Other,” which includes buildings that combine agriculture, industrial activity, or residential functions with other types of commercial buildings (i.e. mixed-use buildings), categorizes buildings such as airplane hangars, telephone switching facilities, and data centers/server farms. To this category, the NEMS definition of “Other” adds Public Order and Safety (i.e. police and military) commercial buildings, vacant commercial buildings, and all commercial buildings not otherwise categorized. Interestingly, this amalgamation of so many diverse building types contributes significantly to subsidy-driven LED growth in the mid-term of the forecast for the New England and Mid-Atlantic regions. In no other regions or time periods do the Other-typed buildings play a large role in subsidy-driven LED growth. Moreover, Other-typed buildings are relatively low users of light – EIA data show Other-typed buildings barely exceeding the national average light usage for all commercial buildings. The average includes vacant buildings, which if removed would make the light usage ranking of Other-typed buildings look even less intensive than the

national average.⁴⁸ The finding adds further weight to the counterintuitive idea that lighting usage alone does not drive the cost-savings benefits that motivate subsidy-driven LED adoption. Beyond that idea, the finding shows further discrepancies between the regions in terms of building types – the northern and eastern regions seem to have strong opportunities for intermediate-term LED growth in Other-typed buildings, while southern and western regions seem to have no such opportunity. Table 23 summarizes the comparisons of LED adoption trends between each of the four regions.

Table 24: Summary of comparisons between LED adoption trends observed in each of the four regions

| Time dimension | Region | | | |
|----------------------------|---|--|--------------------|--|
| | New England | Mid Atlantic | West South Central | Pacific |
| Early period | “Other” building type exhibits strong late-term LED adoption | “Other” building type exhibits strong late-term LED adoption | | |
| Intermediate period | Mercantile & Service, Small Office, and Large Office buildings dominate in the intermediate/late periods. | | | |
| | | Warehouses dominate LED adoption in mid-term | | |
| Late period | Healthcare building show early term LED adoption | | | Healthcare building show early term LED adoption |

5.5.2 Supply-side results: Power sector investment and operations for four regions

⁴⁸ Ibid.

5.5.2.1 1 - New England

Figure 34 shows the change in total resource cost categories within Division 1 – New England under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each total resource cost category is represented as a share of the change in the region’s total resource cost. The total resource cost categories Purchased Power, Fuel Expenses, and Installed Capacity constitute the greatest share of change in total resource costs. Purchased Power costs make up most of the cost savings throughout the forecast period, with fuel expenses a close second. Installed Capacity show a pattern of savings in earlier years but net losses in later years due to postponement of plant construction.

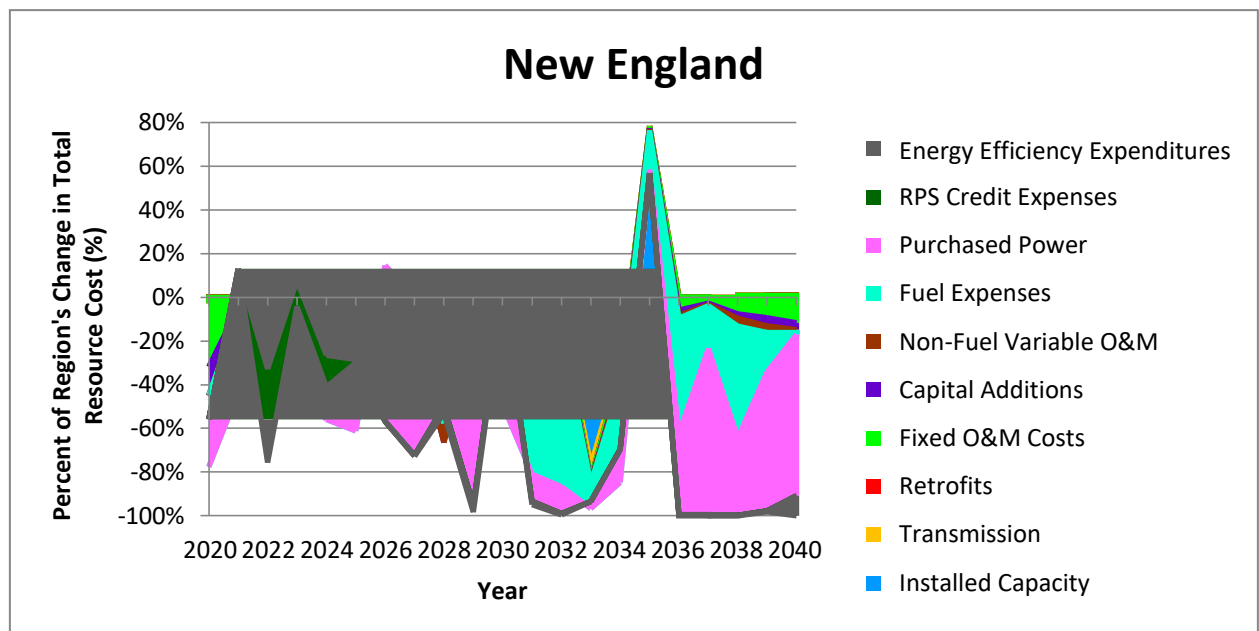


Figure 34: For New England, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories

Figure 35 shows the change in electric power capacity types within Division 1 – New England under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each

electric power capacity type is represented as a share of the change in the region's total electric power capacity. The electric power capacity savings are dominated by the Coal and Combined Cycle capacity types, indicating that LED adoption largely avoids construction of additional coal-fired steam generators and gas-fired combined cycle generators. Oil and Natural Gas Steam constitutes a small share of late-term capacity savings as well.

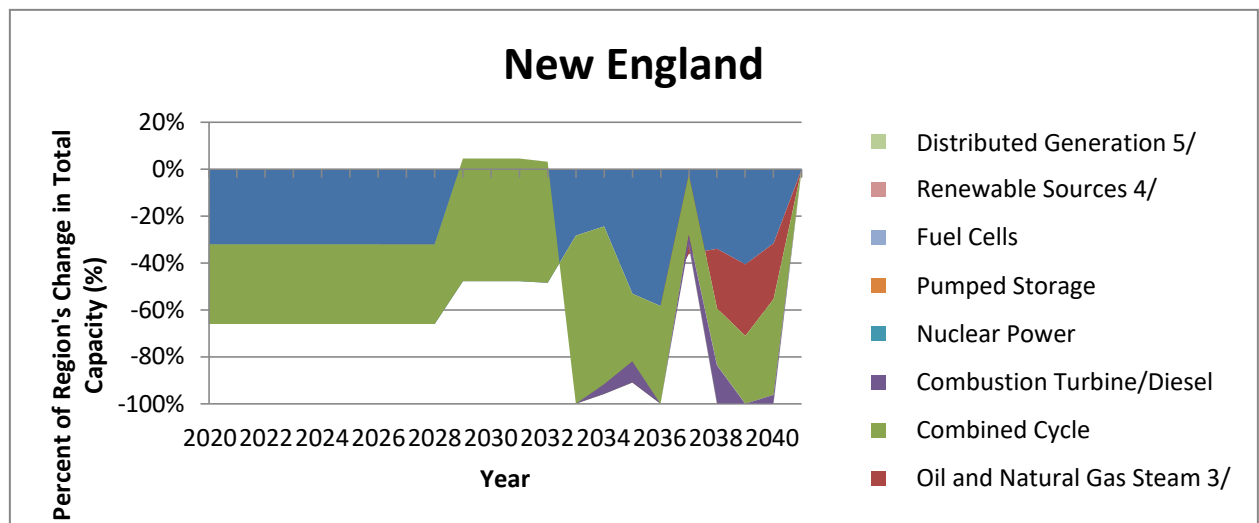


Figure 35: For New England, the share of total change in capacity attributed to each electric power capacity type

5.5.2.2 2 – Middle Atlantic

Figure 36 shows the change in total resource cost categories within Division 2 – Middle Atlantic under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each total resource cost category is represented as a share of the change in the region's total resource cost. Total resource cost categories of Installed Capacity and Fuel Expenses dominate the changes in total resource costs but exhibit great volatility throughout the forecast in oscillating from savings to net losses. Installed Capacity shows several instances of cost savings followed by punctuated net cost increases, indicating several instances of

postponed new capacity construction. Fuel Expenses largely follow Installed Capacity. Interestingly, Energy Efficiency Expenditures contribute a significant share of the total resource cost savings in the forecast's early term, indicating that utilities are spending less on energy efficiency programs thanks to the wider government subsidy for LEDs.

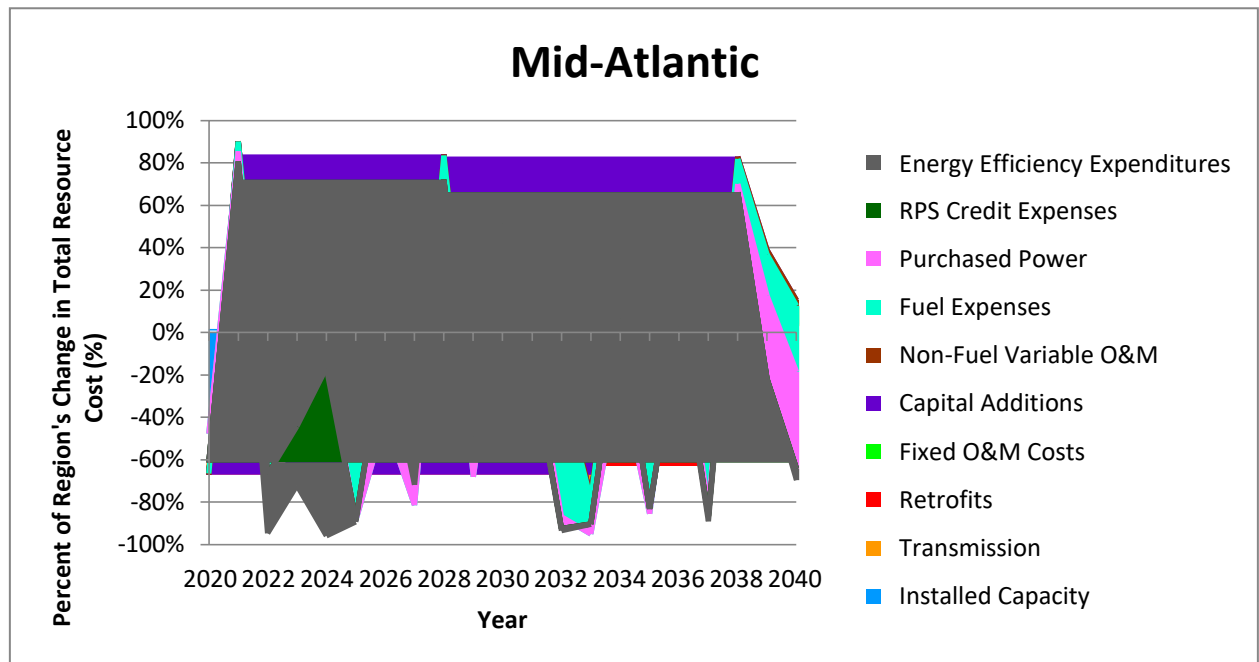


Figure 36: For Mid-Atlantic, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories

Figure 37 shows the change in electric power capacity types within Division 2 – Middle Atlantic under the CPP_AIIIRS scenario relative to the CPP_AIIIRSG scenario. Each electric power capacity type is represented as a share of the change in the region's total electric power capacity. Throughout the intermediate term of the forecast, most of the positive and negative changes in capacity are dominated by Renewable Sources. In the late term, however, Combined Cycle capacity dominates an increase in overall capacity growth. The

volatile trends in Mid-Atlantic capacity changes, particularly for renewable resources, provide explanation for the volatile trends in Mid-Atlantic total resource cost changes.

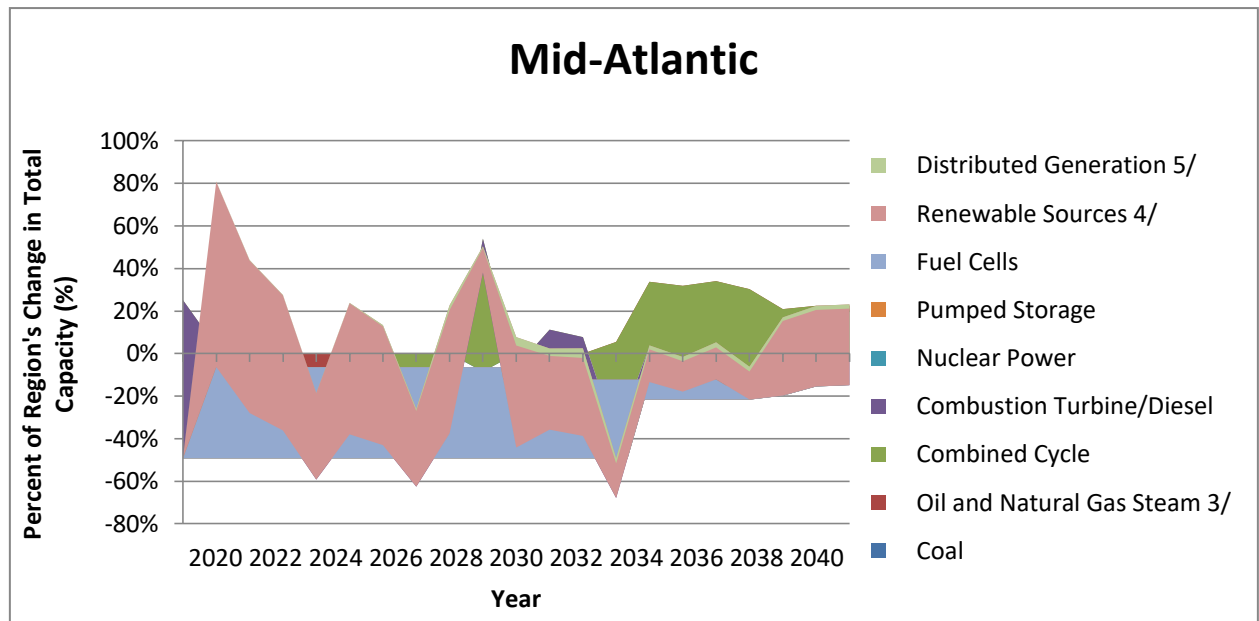


Figure 37: For Mid-Atlantic, the share of total change in capacity attributed to each electric power capacity type

5.5.2.3 7 – West South Central

Figure 38 shows the change in total resource cost categories within Division 7 – West South Central under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each total resource cost category is represented as a share of the change in the region's total resource cost. Total resource cost categories of Purchased Power, Fuel Expenses, and Installed Capacity dominate the changes but exhibit great volatility throughout the forecast in oscillating from savings to net losses. In some years cost increases in Installed Capacity are accompanied by cost increases in Purchased Power and Fuel Expenses, but in other years Purchased Power or Fuel Expenses exhibit cost increases without any accompanying cost increases from Installed Capacity. The forecast shows many instances of Installed

Capacity exhibiting savings in early years but net losses in later years, indicating that increased LED adoption has postponed several new capacity constructions but has not fully mitigated them.

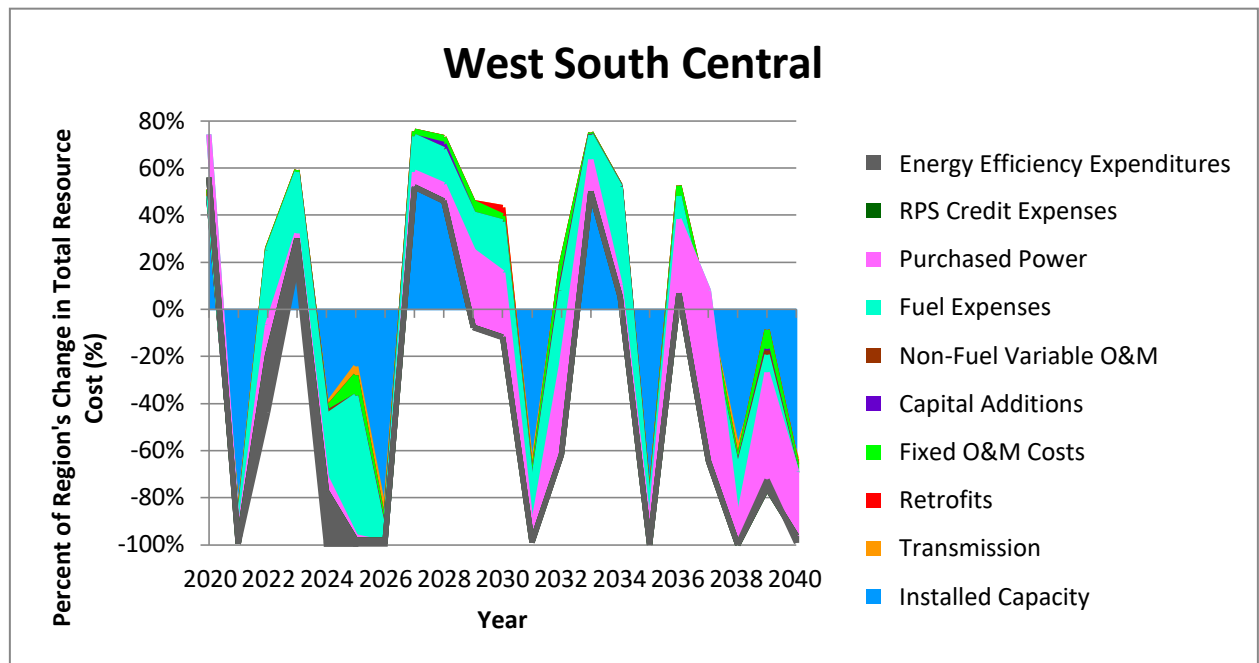


Figure 38: For West South Central, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories

Figure 39 shows the change in electric power capacity types within Division 7 – West South Central under the CPP_AIIRS scenario relative to the CPP_AIIRSG scenario. Each electric power capacity type is represented as a share of the change in the region’s total electric power capacity. In the early term, Renewable Sources dominate the changes in total capacity, and overall there are fewer Renewable Sources under the CPP+Subsidy scenario in the early term. Oil and Natural Gas Steam makes up the largest share of capacity savings in the intermediate and late term, with Combined Cycle contributing a small share

in the late term as well. The lack of increases in total capacity throughout most of the intermediate and late term of the forecast signifies that total resource cost increases during this period are attributable to new resources that are built to replace existing resources that have retired and been de-commissioned. Since Installed Capacity costs increase but total capacity does not, it follows that the Installed Capacity expenditures are being used to replace retiring generators.

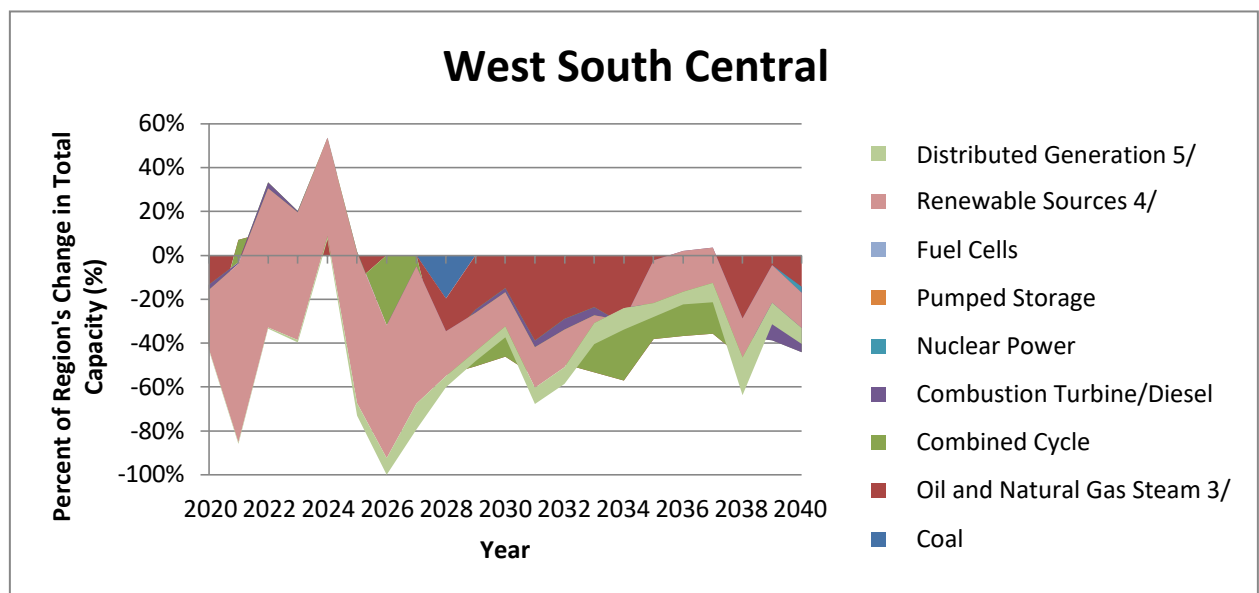


Figure 39: For West South Central, the share of total change in capacity attributed to each electric power capacity type

5.5.2.4 9 – Pacific

Figure 40 shows the change in total resource cost categories within Division 9 – Pacific under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each total resource cost category is represented as a share of the change in the region's total resource cost. Fuel Expenses and Installed Capacity dominate the cost savings. Purchased Power exhibits net

cost increases in early years of the forecast. Installed Capacity exhibit patterns of cost savings in early years followed by punctuated net cost increases in later years, indicating some postponement of capacity construction.

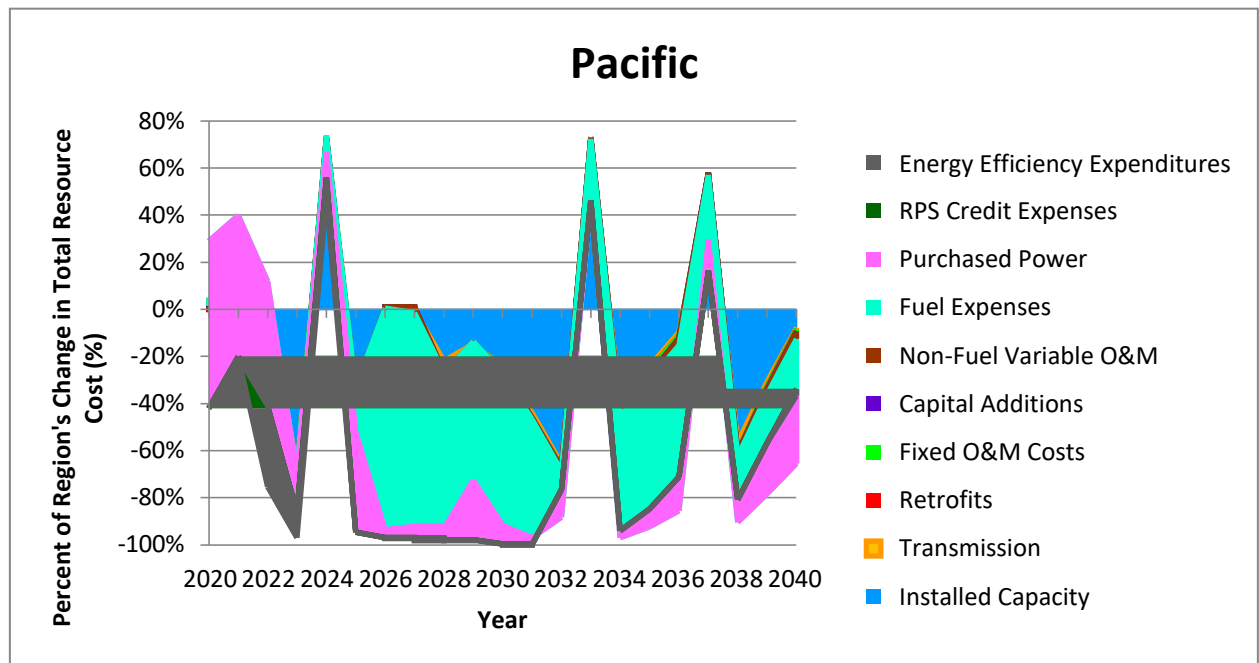


Figure 40: For Pacific, the percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories

Figure 41 shows the change in electric power capacity types within Division 9 – Pacific under the CPP_AllRS scenario relative to the CPP_AllRSG scenario. Each electric power capacity type is represented as a share of the change in the region's total electric power capacity. Renewable Sources dominate the early-term and intermediate-term changes in capacity under the CPP+Subsidy scenario. Through 2030, all reductions in total capacity can be attributed to reduced capacity from Renewable Sources. In the late-term, however, total capacity savings becomes dominated by savings in Combined Cycle capacity. Net

increases in total resource cost without accompanying increases in total capacity during the late-term of the forecast imply that new capital costs are being incurred in the late term for the construction of replacement capacity for retiring units.

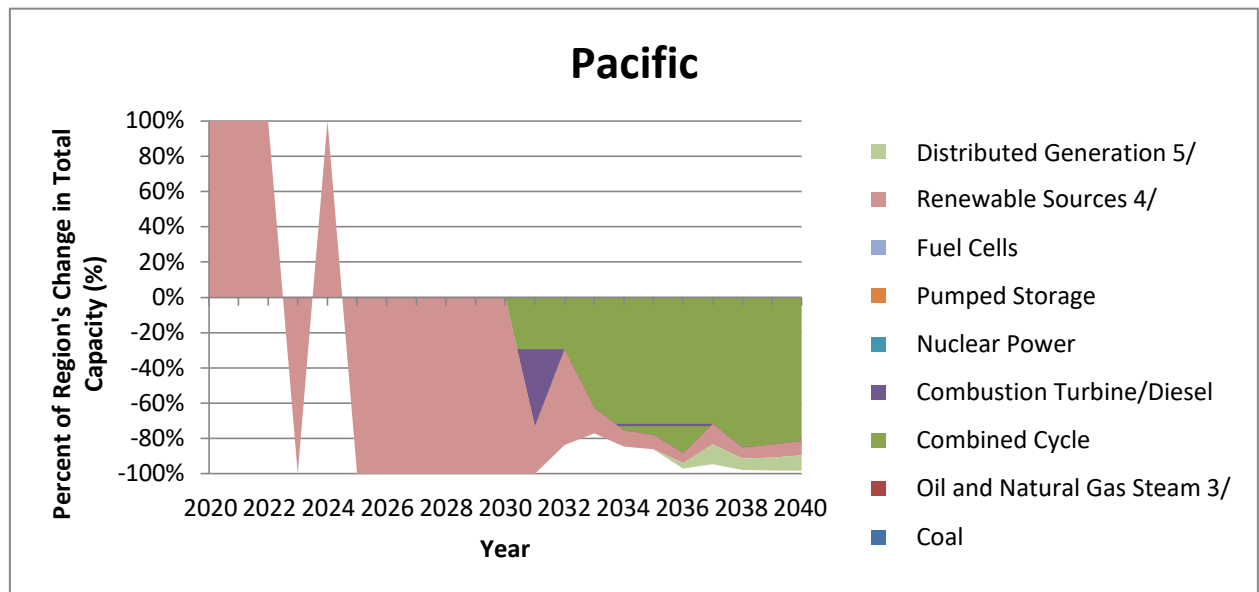


Figure 41: For Pacific, the share of total change in capacity attributed to each electric power capacity type

5.5.2.5 Comparisons: Supply-side changes

Comparing results from the four regions reveals several interesting findings regarding the impacts of subsidy-driven LED adoption on power sector outcomes, especially given the finding that all four regions adopt similar levels of LEDs as percentages of each region's total lighting service demand. In some regions, LED adoption reduces the growth of Renewables and Combined Cycle generators in the late term, showing how efficient electric power consumption can compete with growth in new “clean” infrastructure. While some regions fully mitigate new capacity builds through LED adoption, other regions exhibit investment-shifting forward in time – suggesting that for some regions new

infrastructure postponement is possible, but that new infrastructure construction may be inevitable. Thanks to the Clean Power Plan compliance assumed in the subsidy scenario, however, much of the new construction consists of relatively low-carbon-intensive capacity. Finally, only one region – the Mid-Atlantic Region – shows the interesting result of subsidy-driven LED adoption crowding out utility spending on energy-efficiency programs, showing an unexpected effect for a region with high energy efficiency program spending.

The results enable the following specific regional comparisons of the different financial and infrastructure outcomes while having similar levels of subsidy-driven LED adoption. As for costs, while Purchased Power cost savings make up a large portion of the total cost savings experienced by the New England and West South Central regions, the Pacific and Mid-Atlantic regions save a much smaller amount of Purchased Power costs. The New England region experiences cost savings in almost all years, while the Pacific, West South Central, and Mid-Atlantic regions show a volatile pattern of savings alternating with cost increases year over year – indicating a greater degree of capacity postponement rather than mitigation in the latter three regions. The Mid-Atlantic is the only region to exhibit a significant portion of cost savings coming from reduced utility spending on energy efficiency programs. As for infrastructure, the regions exhibit several differences as well. Only the New England and West South Central regions’ subsidy-driven LED adoption appears to cause reductions in coal-fired capacity, and the share of total capacity reduction attributed to coal-fired capacity is much smaller in West South Central than in New England. The New England and West South Central regions both also exhibit a substantial share of total capacity reductions coming from Oil and Gas Steam units. Conversely, for the Mid-Atlantic and Pacific regions, most of the reductions in total capacity come from Renewable Sources and Combined Cycle units, yielding the

interesting finding that LED adoption may compete with low-carbon resources only in certain regions of the US. Only the Pacific and West South Central regions exhibit a pattern of cost and capacity changes indicating large amounts of new infrastructure being built to replace retiring generating units. By contrast, the Mid-Atlantic and New England regions' costs largely correlate with capacity additions, indicating new construction that subsidy-driven LED adoption has postponed. Table 24 summarizes the comparison of observed trends.

Table 25: Summary of electric power sector trends resulting from LED adoption observed in each of the four regions

| Time Dimension | Region | | | |
|-------------------------------|--|--|--|--|
| | New England | Mid Atlantic | West Central | South Pacific |
| Early period | | subsidy-driven LED adoption crowds out utility spending on efficiency programs | | |
| Intermediate period | | | substantial reductions of Oil and Gas Steam units | |
| | reductions in coal-fired capacity | | reductions in coal-fired capacity | |
| Late period | substantial reductions of Oil and Gas Steam units | | | |
| | Reduced growth for Renewables and Combined Cycle generators in the late term | | Reduced growth for Renewables and Combined Cycle generators in the late term | |
| Entire forecast period | Fully mitigates most new capacity builds | | | |
| | | Postpone many new capacity builds | Postpone many new capacity builds | Postpone many new capacity builds |
| | Purchased Power cost savings make up substantial share of total cost savings | | Purchased Power cost savings make up substantial share of total cost savings | |
| | | | Significant expenditures to replace retiring units | Significant expenditures to replace retiring units |

5.5.3 *Grouped results figures*

For comparisons, the charts of results for each of the four regions have been grouped together in the following figures. Figure 42 groups the results for LED adoption, Figure 43 groups the results for total resource cost categories, and Figure 44 groups the results for electric power capacity types.

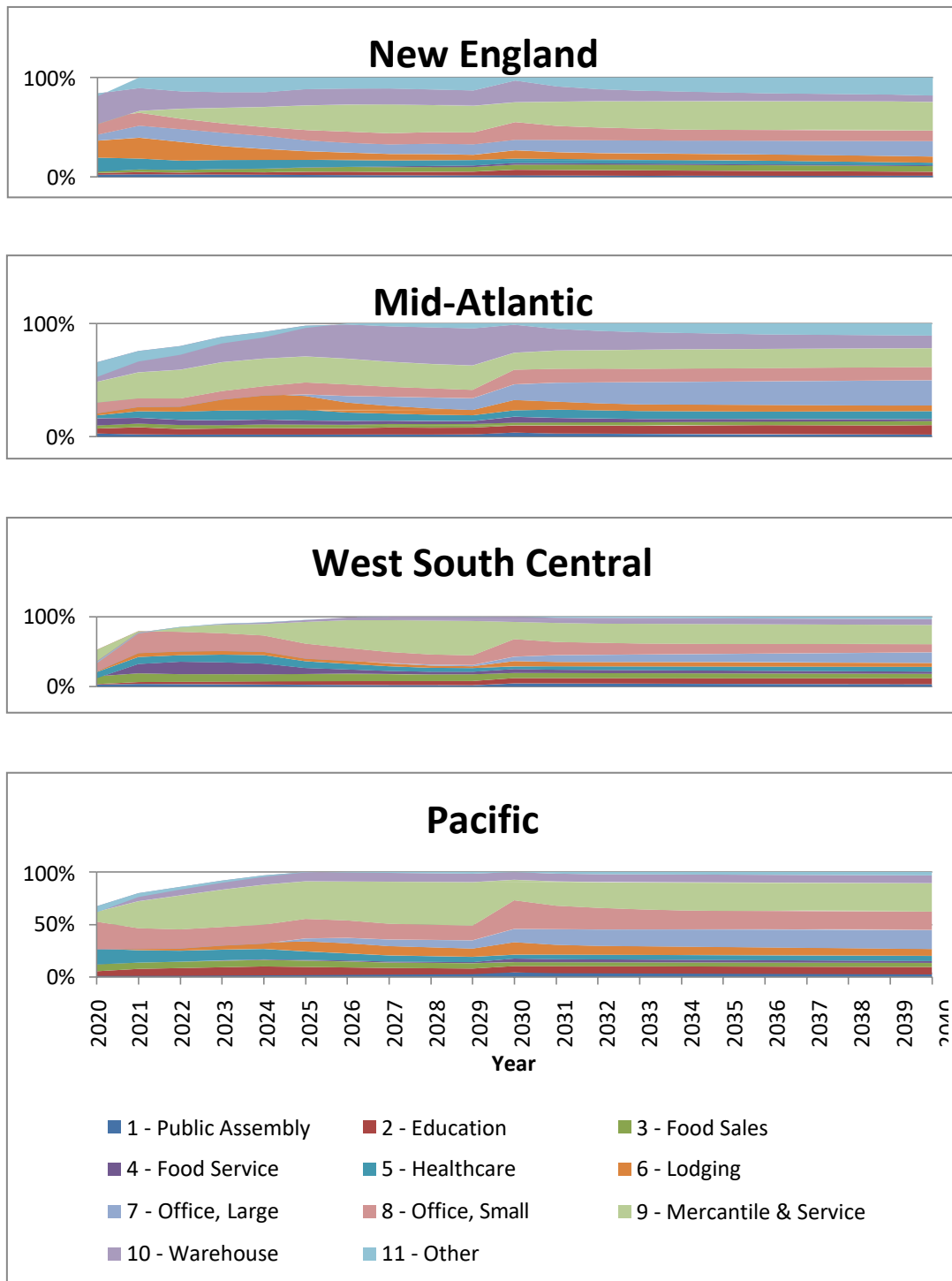


Figure 42: All regions' results: Percent of the increase in service demand met by LEDs under the CPP+Subsidy scenario relative to the CPP-only scenario attributable to each of the eleven building types

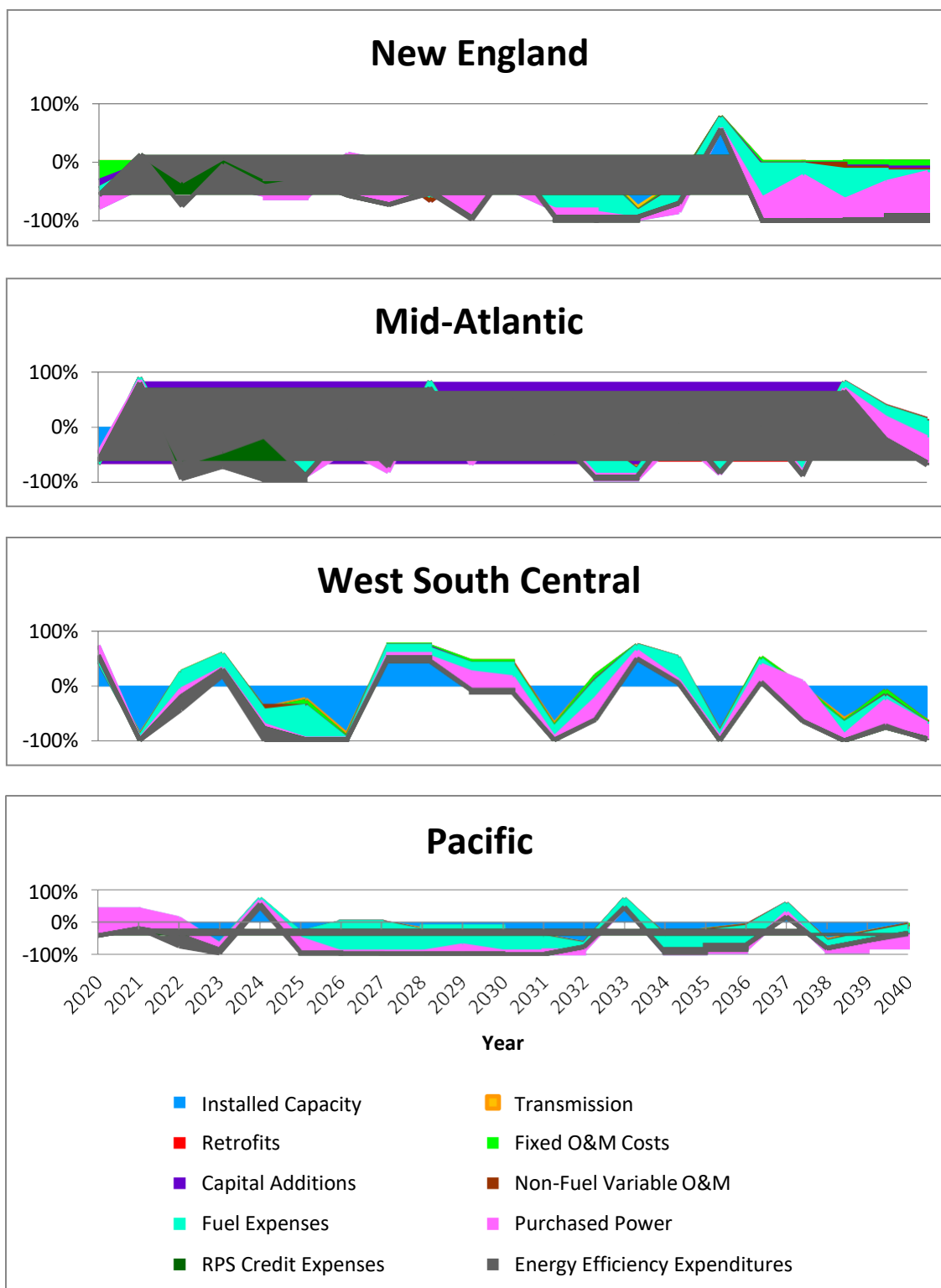


Figure 43: All regions' results: Percent of total resource cost changes between the CPP+Subsidy scenario and the CPP-only scenario attributable to each of the total resource cost categories

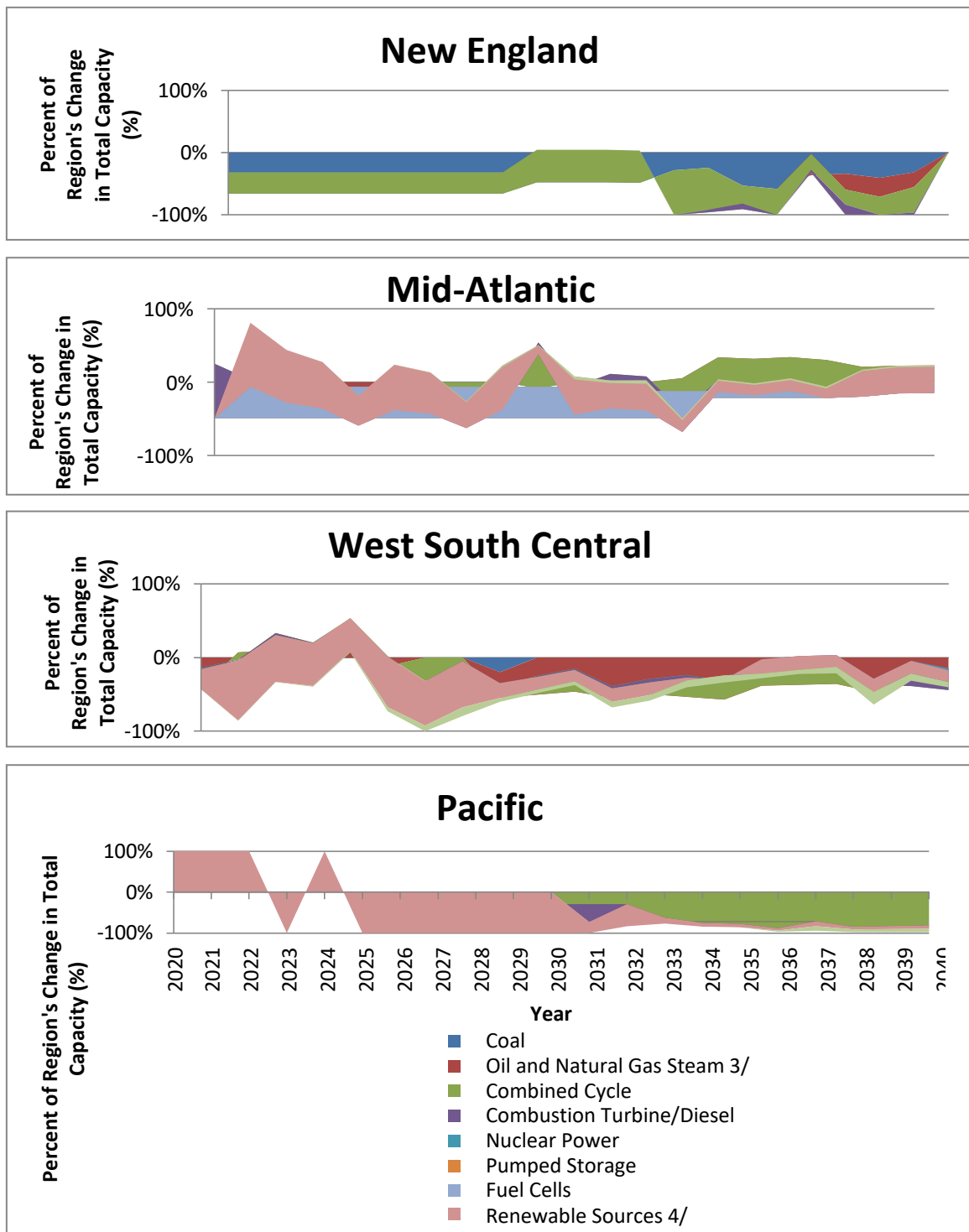


Figure 44: All regions' results: The share of total change in capacity attributed to each electric power capacity type

5.6 Conclusion

5.6.1 *Summary of main findings*

The relevance of differences in the buildings infrastructure and electric power sector infrastructure between US regions becomes quite clear from the findings in this analysis. Specifically, and most importantly, each of the four regions examined adopts a similar level of LEDs in terms of the region's total lighting demand met by LED technologies. By 2040, the analysis finds that each region meets approximately 20% of its lighting demand through LED technologies. Despite the similarity in level of LED adoption, however, each region's electric power sector exhibits its own distinct response. Some regions such as New England respond to reduced demand by reducing imported energy (Purchased Power) while other regions respond to savings with a greater proportion of reductions in their own generation (Fuel Expenses). Some regions such as the Pacific and West South Central regions are able to reduce total capacity but still incur new construction costs (Installed Capacity) due to a need to replace retiring generators. Distinct from other regions, the Mid-Atlantic exhibits a large number of instances of postponed new generator construction. Moreover, where LED adoption reduces the region's electric power total capacity, the type of total capacity reduced varies significantly by region as well. The New England region exhibits a uniquely large share of reductions in coal-fired capacity, while the Mid-Atlantic and Pacific regions exhibit large reductions in renewable sources. The West South Central region exhibits a relatively diverse portfolio of capacity reductions coming from subsidy-driven LED adoption, including reductions in renewable capacity, oil and gas steam-powered capacity, and coal-fired capacity.

The diversity of impacts leads to a rejection of some of the study’s hypotheses and failure to reject some of the study’s hypotheses. Table 25 organizes the verdicts delivered on each of the study’s hypotheses.

Table 26: Hypotheses, findings, and decision to reject or fail to reject each hypothesis

| Hypothesis | Findings | Reject, Fail to Reject, Future Research Needed |
|--|--|--|
| 1: Building types that are the most intensive users of lighting will exhibit the greatest LED adoption | Buildings with most intense lighting usage show relatively low LED adoption; Buildings with intermediate lighting usage show relatively high LED adoption | Reject |
| 2: Holding LED adoption constant, power sector outcomes will vary by region due to the influence of path-dependent factors | Each region has a unique pattern of trends in both LED adoption and the resulting power sector outcomes | Fail to Reject |
| 3: Greater LED adoption will result in lower total resource cost | Most regions exhibit patterns of postponed costs – i.e. one year showing LED adoption reducing costs and then the subsequent year showing LED adoption increasing costs. Only one region shows mostly reductions in total resource costs in all years. | Reject; Future Research Needed to explore why most regions postpone costs but one region is able to mitigate costs. |
| 4: Greater LED adoption will displace high-emitting power sources | Some regions show substantial displacement of high-emitting power sources, but other regions show displacement of low-emitting power sources instead | Reject |

5.6.2 *Why the findings are novel and interesting*

The novelty of the study's findings is grounded in the study's novel methodology. While most studies of electric power sector emissions apply different policies to observe emissions reductions outcomes, this study takes a novel approach by holding emissions reductions constant and observing variation in compliance costs under different scenarios. By allowing the examined regions to achieve CPP compliance in all scenarios and allowing compliance costs to vary by scenario, the study exposes relationships LED adoption has with the cost of CPP compliance and power sector operations. Finally, while the literature generally finds that efficient energy-consuming technologies provide cost-competitive options for reducing CO₂ emissions, the analysis presented here adds nuance by illustrating heterogeneous, path-dependent, region-specific impacts of introducing efficient technologies. The study's comparison of regional LED adoption to Total Resource Cost (TRC) and electric power capacity outcomes under CPP compliance with a subsidy to LED technologies reveals the regional differences that add nuance to nation-level findings, such as that presented in Brown et al (2017).

This study's novelty and its connection to the study's novel methodology also rests with improvements to GT-NEMS' representation of SSL technologies and the novel subsidy policy implemented in GT-NEMS. Prior work has made use of GT-NEMS representation of interactions between the energy consumption sectors and the electric power sector's greenhouse gas emissions policies (Brown et al 2017), which already represents a novel improvement over competing studies. However, this prior work has not included an accurate, empirically grounded characterization of SSL technologies for commercial building applications. This study provides such a characterization, involving copious data collection from existing works characterizing current and expected improvements in

commercial buildings' SSL products. Moreover, prior work has not included a nation-wide subsidy policy whose representation requires the use of specific modeling capabilities possessed only by GT-NEMS. Prior work has also not yet combined that subsidy modeling with modeling to represent a cap on power sector emissions. Both the subsidy modeling and the combination of subsidy modeling with power emissions cap modeling represent unique and novel contributions of this study.

5.6.3 Takeaways for policy-making

The diverse responses of regions to a single nation-wide policy offer several useful policymaking takeaways. Electricity efficiency is rarely done for its own sake and generally toward the ends of more-desired outcomes policymakers expect to be delivered from electricity efficiency – such as co-pollutant reduction, cost savings to consumers, and the development of new industries such as renewable electric power. With those ends in mind, the results of this study prompt greater caution and forethought among policymakers. For example, policymakers seeking to grow a region's renewable electric power industry should carefully consider whether policies subsidizing LEDs or electric power savings in general might foreclose future opportunities to grow a region's renewable generation. The examples of the Mid-Atlantic and the Pacific regions in this study make it clear that LED adoption can displace renewable resources in some regions, while the example of the New England region shows that LEDs might not displace renewable generation in other regions. Similarly, policymakers seeking to reduce non-carbon pollutants from electric power generation should make a consideration of whether policies subsidizing LEDs might reduce demand in regions supplied largely by renewable generation, leading to minimal reductions in non-carbon pollutants. Regions such as the Mid-Atlantic and Pacific, where LED

adoption displaces mostly renewable generation, accompanying non-carbon pollution reduction may be rather slight compared to regions such as New England wherein LED adoption displaces coal-fired capacity. Next, policymakers seeking to reduce costs of electric power infrastructure should consider whether their region must undergo new construction or replacement construction. If future costs of power infrastructure are expected to come from replacement construction, as found in the West South Central region, LED adoption may not satisfy the aims of avoiding future construction costs. Conversely, in regions such as the New England and Mid-Atlantic regions, LED adoption avoids or postpones new construction and the associated costs, illustrating the role of path-dependent regional infrastructure in determining the degree to which LED adoption (and energy efficiency more broadly) can achieve policymaker's cost reduction goals. Moreover and perhaps most surprising, policymakers seeking to lower electric power bills paid by hospitals and schools should carefully consider how well a subsidy to LEDs in general will achieve this goal – given this study's finding that, despite being large users of lighting products, hospitals and schools are nowhere near the largest adopters of subsidized LEDs, which in fact are office buildings and stores.

Policymakers intending to use energy efficient products such as LEDs to affect long-term pollution and cost outcomes from the electric power sector should account for the electric power sector's extreme path-dependencies. Policymakers should design policies to account for the intervening effects of that path-dependent infrastructure – lightbulb subsidies may not be a one-size-fits-all solution.

In designing policies that account for path-dependent electric power infrastructure when pursuing the goals of pollution reduction, cost savings, and renewable energy generation,

policymakers fortunately have many alternatives to consider. Policymakers seeking to reduce the costs of constructing new or replacement power plants could consider policies that enable competitive solicitation for replacement construction and policies that encourage knowledge-sharing across utilities to facilitate access to low-cost replacement technologies. Policymakers seeking to reduce carbon emissions from power plant operation might target power imports instead of domestic generation if imported power is more carbon-intensive than domestic generation; domestic energy efficiency (e.g. lightbulb subsidies) may not be the best path in such a case, and encouraging growth in clean domestic generation to reduce dependence on dirtier imported power might be a better option. Policymakers seeking to reduce local pollutants should contemplate the energy infrastructure that energy-efficiency-driven reductions in demand would displace – if the infrastructure is new renewable generation, lightbulb subsidies may not be the most effective means of reducing local pollution. Technology standards or pollution taxes may be a more effective means of pursuing this goal.

CHAPTER 6. CONCLUSIONS AND PROSPECTS ON LIGHTING TECHNOLOGY PATHS TAKEN AND YET TO BE TAKEN

6.1 Lessons from Path-dependency analyses of lighting innovation policies

6.1.1 *Path-dependency in firms: Core Capabilities can frustrate policies fostering inter-firm collaboration for technology development*

When faced with the question of why Hewlett-Packard's spin-out Agilent abandoned its LED joint-venture with Phillips, Nelson and Winter's evolutionary theory of economics provides key explanatory insights. This study examined relevant data on each firm's early history, decision-making routines, and collaboration behavior during the 1980s, finding links between each firm's established decision-making routines (i.e. "Core Capabilities") and each firm's 1980s inter-firm collaboration. The study finds that Nelson and Winter's hypotheses regarding evolutionary economics hold under evidence from the histories of Hewlett-Packard, Philips, and each firm's inter-firm collaboration behavior. Moreover, the study finds that the specific history of Agilent and its Core Capabilities inherited from Hewlett-Packard explain the decision by Agilent to abandon its joint-venture with Philips in 2005.

Policymakers who design policies to affect R&D performed by firms and academics who study R&D performed by firms should care about this chapter because it reveals a key latent factor, Core Capabilities, that affects how a firm performs R&D and whether it will collaborate on R&D with other firms. This chapter highlights how Core Capabilities hampered the collaboration between two firms, Hewlett-Packard and Philips, on

developing new technology for SSL. Hewlett-Packard and Philips were an ideal match for developing SSL technology and assisting SSL innovation because of Hewlett-Packard's expertise in optics and solid-state materials and Philips' expertise in designing and manufacturing consumer lightbulbs. Moreover and more importantly, many policies had been put into place to foster inter-firm collaboration, a major policy shift from the post-World-War-II era in which inter-firm collaboration within the US had been discouraged by policy. Yet despite policies favoring an advantageous case of interfirm R&D collaboration, Hewlett-Packard and Philips collaborated through a joint-venture only a short while before Hewlett-Packard abandoned the joint-venture and SSL altogether. The analysis presented in this chapter reveals that Core Capabilities were to blame for the infringed collaboration between Hewlett-Packard and Philips.

Since this chapter's analysis reveals a factor affecting firms' R&D performance, policymakers and academic researchers focusing on this area should alter their policy designs and research designs accordingly. Policymakers should take assessments of the Core Capabilities of the firms whose R&D they seek to influence and design policies so as to take advantage of – or at least not get thwarted by – firms' Core Capabilities. In a similar manner, academic researchers interested in what drives firm R&D should look further into the Core Capabilities of firms of interest. Researchers should account for a firm's Core Capabilities when estimating the influence of any other factor on the firm's R&D performance. Moreover, publicizing analyses that establish individual firms' Core Capabilities would be of great use to policymakers seeking to design policies influencing those firms' R&D.

6.1.2 *Path-dependency in patenting: Appropriability Regimes can frustrate policies fostering technology sharing through patent production and licensing*

Overall, the study's evidence from sampled researchers' patenting behavior indicates support for a path-dependent explanation for reduced patenting in the face of a policy designed to spread knowledge embodied in patented technologies. Teece's Appropriability Regimes hypothesis holds and provides part of the explanation, but there are further nuances – specifically with regards to which sector a researcher is working in. As with related path-dependency studies, the path-dependency focus helps highlight factors that have contributed to countervailing effects against policy design and, in so doing, aid the design of more effective policies for change.

The study's use of a path-dependency framework highlighted path-dependent variables such as Appropriability Regimes that fluster innovative R&D policies. The study illustrates the influence of path-dependency on outcomes from innovative policies stimulating innovation in the lighting sector. By applying path-dependency to patent licensing requirements, the study builds upon prior findings in path-dependency. In highlighting factors that frustrate the aims of contemporary innovation policies towards lighting, this dissertation aims to inform the design of future innovation policies such that future policies may account for influential factors and design strategies that nullify or take advantage of such factors to enact change.

As with any study of path-dependency, the overall finding must be one of nuance. A policy attempting to force sharing of patents may not necessarily discourage patent production in every case, but may have disparate impacts among those affected because of path-

dependent factors governing patent production. Theory predicted that the forced sharing of patents would discourage the affected parties from producing patents, but only in certain cases did this turn out to be true. We can conclude, for example, that if the DOE SSL Program expected technology expedition to occur through forced sharing of patents produced by Lighting-industry-affiliated investigators, the program may have defeated itself through a policy that discouraged Lighting-industry-affiliated investigators from producing patents. Conversely, if the DOE SSL Program held the same expectation for Materials-industry-affiliated investigators, the program may rest easy knowing that its Compulsory Licensing policy is not likely to have defeated this goal. Moreover, if the program hung its hopes on patents produced by Small Firms, the program needn't worry – unless the program had specifically hoped for small, California-based startups to acquire and then share patents. This study has revealed many such nuances in the relationship between policies for forced patent sharing and affected parties' decisions to produce patents. The study underscores the fact that path-dependency concepts help researchers understand the factors and patterns that have contributed to persistent circumstances and in so doing aids the design of more effective policies for change. The study uses a path-dependency research lens to highlight factors that an innovative policy effort did not capture and aids in the crafting of more effective means of creating change.

6.1.3 *Path-dependency in buildings and power grids: Existing infrastructure can frustrate policies for lighting adoption and electricity cost reductions*

Analyzing the differences in regional responses to policies promoting SSL technology adoption provides many useful takeaways for policy-making. Electricity conservation is rarely done for its own sake and generally toward the ends of more-desired outcomes

policymakers expect to be delivered from electricity conservation – such as co-pollutant reduction, cost savings to consumers, and the development of new industries such as renewable electric power. With those ends in mind, the results of this study prompt greater caution and forethought among policymakers. For example, policymakers seeking to grow a region’s renewable electric power industry should carefully consider whether policies subsidizing LEDs or electric power savings in general might foreclose future opportunities to grow a region’s renewable generation. The examples of the Mid-Atlantic and the Pacific regions in this study make it clear that LEDs adoptions can displace renewable resources in some regions, while the example of the New England region shows that LEDs might not displace renewable generation in other regions. Similarly, Policymakers seeking to reduce non-carbon pollutants from electric power generation should make a consideration of whether policies subsidizing LEDs might reduce demand in regions supplied largely by renewable generation, leading to minimal reductions in non-carbon pollutants. Regions such as the Mid-Atlantic and Pacific, where LED adoption displaces mostly renewable generation, accompanying non-carbon pollution reduction may be rather slight compared to regions such as New England wherein LED adoption displaces coal-fired capacity. Next, policymakers seeking to reduce costs of electric power infrastructure should consider whether their region must undergo new construction or replacement construction. If future costs of power infrastructure are expected to come from replacement construction, as found in the West South Central region, LED adoption may not satisfy the aims of avoiding future construction costs. Conversely, in regions such as the New England and Mid-Atlantic regions, LED adoption avoids or postpones new construction and the associated costs, illustrating the role of path-dependent regional infrastructure in determining the degree to

which LED adoption (and energy efficiency more broadly) can achieve policymaker's cost reduction goals. Moreover and perhaps most surprising, policymakers seeking to lower electric power bills paid by hospitals and schools should carefully consider how well a subsidy to LEDs in general will achieve this goal – given this study's finding that, despite being large users of lighting products, hospitals and schools are nowhere near the largest adopters of subsidized LEDs, which in fact are office buildings and stores.

In designing policies that account for path-dependent electric power infrastructure when pursuing the goals of pollution reduction, cost savings, and renewable energy generation, policymakers fortunately have many alternatives to consider. Policymakers seeking to reduce the costs of constructing new or replacement power plants could consider policies that enable competitive solicitation for replacement construction and policies that encourage knowledge-sharing across utilities to facilitate access to low-cost replacement technologies. Policymakers seeking to reduce carbon emissions from power plant operation might target power imports instead of domestic generation if imported power is more carbon-intensive than domestic generation; domestic energy efficiency (e.g. lightbulb subsidies) may not be the best path in such a case, and encouraging growth in clean domestic generation to reduce dependence on dirtier imported power might be a better option. Policymakers seeking to reduce local pollutants should contemplate the energy infrastructure that energy-efficiency-driven reductions in demand would displace – if the infrastructure is new renewable generation, it lightbulb subsidies may not be the most effective means of reducing local pollution. Technology standards or pollution taxes may be a more effective means of pursuing this goal.

6.2 Implications for Path-dependency: Contributions to existing academic debates

Beyond informing policymaking, the studies in this dissertation make contributions to path-dependency theory on par with contributions made by published academic journal articles and filling crucial gaps in the literature. While the important factors revealed through the path-dependency analyses presented in this dissertation have important implications for policymaking, the dissertation's studies contribute to path-dependency theory through unique applications of path-dependency to new areas. As shown in Chapter 2's literature review, academic literature on path-dependency contains several crucial gaps in terms of how and to what topics path-dependency analysis has been applied. Each study presented in this dissertation involves an original and novel application of path-dependency analysis and thus expands the scope of the theory. Moreover, as shown in Chapter 2's review of literature on path-dependency, published academic journal articles frequently serve the purpose of using path-dependency analysis to contribute a new factor that explains failure to innovate. Chapters 3, 4, and 5 of this dissertation perform exactly that task and thus make contributions on par with published journal articles.

Chapter 3's analysis expands the domain of path-dependency theory to the new topic of joint ventures and brings novel content to the theory by focusing on entire firm histories. As written in Chapter 3, joint ventures have been a common topic of research in the management science and business history fields, but these fields have not applied the path-dependency analysis framework to exploring the causes and effects of joint ventures. The path-dependency analysis framework has only seen one application to joint ventures—a study by Pajunen & Fang (2013), which focuses on the beginnings and endings of joint ventures between Finnish and Chinese firms. However, Pajunen & Fang's study only focuses on how early events during a joint venture's history create lock-in effects that

influence events later in that joint venture's history. Pajunen & Fang's work does not examine the histories of the respective firms coming to the joint venture and does not incorporate those histories into explaining outcomes of a joint venture. This leaves a gap in the literature – an application of path-dependency that examines the whole history of firms involved in a joint venture. Chapter 3's analysis fills this gap by applying a path-dependency analysis that encompasses the whole scope of Hewlett-Packard's and Philips' respective histories. In so doing, Chapter 3 provides a contribution to path-dependency theory similar to that made by several published academic journal articles by contributing Core Capabilities as a new factor that explains the failure of joint ventures.

Chapter 4's analysis not only explores a novel topic but also brings path-dependency analysis to that topic for the first time. Chapter 4's analysis is novel without the addition of path-dependency in that Chapter 4's analysis studies a compulsory licensing policy for a specific technology. As noted in the literature review, most studies of compulsory licensing focus on international patent licensing discussed during WTO negotiations, and studies of compulsory licensing outside of this area focus on nation-wide policies. No study focuses on a technology-specific compulsory licensing policy. To this new area of research, Chapter 4 brings path-dependency theory for the first time. No prior study has used the path-dependency framework to analyse patent licensing, and so Chapter 4's analysis expands the domain of path-dependency theory to include not just patent licensing, not just compulsory licensing, but compulsory licensing of patents in a specific technological domain. Beyond meeting the novelty of application standard, Chapter 4 also meets the standard of a published academic article on path-dependency theory by contributing Appropriability Regimes as a factor explaining failure to innovate.

Chapter 5's analysis contributes to the literature on path-dependency in energy systems an entirely new paradigm of forward-looking path-dependency analysis. As shown in Chapter 2's review of literature on the path-dependencies in energy systems, the literature's published academic articles apply path-dependency retrospectively. All studies reviewed involve a historical examination of energy systems' evolution, taking advantage of time that has passed and revealed causes and effects. None of the studies provides a forward-looking approach that could inform policymaking *before* policies are implemented. As shown in the works by Alan Porter and others on forecasting technology pathways, however, path-dependency analysis *can indeed* be applied prospectively. The literature on path-dependency in energy systems has thus lagged the literature on R&D policy by failing to employ a forward-looking approach, leaving a large gap for future work. This is especially important given the strong path-dependencies present in energy systems – these strong path-dependencies make the need for analyses that can advise policymaking prospectively all the more immediate. While there is much potential for forward-looking applications of path-dependency in energy systems, Chapter 5's analysis helps to fill this gap. Moreover, Chapter 5 makes contributions to the literature on par with published academic journal articles. Chapter 5 contributes several counterintuitive findings that reject reasonable hypotheses (and common policymaking assumptions) about how energy systems would behave under expanded adoption of SSL.

6.3 Where is solid-state lighting going to go next?

Having addressed through the Path-dependency Framework some of the history of innovation in lighting, we now turn to discussion of future prospects for SSL. As this section will discuss, the industry has recently seen a homogenization and a single-path for

LED commodity lamps, but new applications and growing markets for SSL specialty products have presented many new paths that SSL technology could take. This section will also discuss how projections of future markets for SSL specialty products add a cautionary note to the technology optimism, however, given the potential for SSL's long lifetimes to reduce sales after an initial global rollout.

6.3.1 *Near-term outlook for solid-state lighting technology*

LED technologies have seen many recent improvements in efficiency and have exhibited a significant increase in adoption rates; moreover, researchers have recently found a wide variety of new applications for LED lighting technologies. Researchers still haven't solved fundamental problems like reduced output ("droop") at high current and unequal thermal efficiency for different LED frequencies, however, so some challenges remain. Moreover, now that subsidized LED commodity lamps have collapsed prices, suppliers show little interest in solving fundamental R&D problems with LED commodity lamps. Instead, recent designs compensate for fundamental problems through such measures as turning on more LEDs when at high currents to compensate for droop. LED flickering under application of a conventional dimmer will also continue to be a challenge and must be overcome to achieve consumer acceptance (*National Academies of Sciences Engineering and Medicine, 2017*).

Several new applications for SSL have recently emerged, and more are likely to in the near future. One popular application that dovetails with related innovations in home networking technologies goes under the umbrella term of "Connected Lighting Systems," in which users can wirelessly control light dimming, color-tuning, and other lighting features of your

home. Connected Lighting Systems vary in complexity – some systems are stand-alone (i.e. only for controlling the lighting in a home) while other systems interface with the internet and anything else connected to the home network (e.g. enabling users to control both the washing machine and the lighting from a single device). Moreover, various Connected Lighting Systems use different wireless protocols for communication, such as ZigBee, Wi-Fi, Bluetooth, or proprietary protocols. A consortium called the Connected Lighting Alliance has endorsed the use of ZigBee 3.0 for Connected Lighting Systems. Conversely, skeptics have raised the issue (common to all home network technologies) that hostile actors could penetrate a Connected Lighting System for harmful purposes (Colon & Torres, 2017; Grau, 2015; Halper, 2016; Moore, 2016).

Some observers have raised concerns regarding the impact of widespread LED adoption, particularly for public lighting applications, on human and environmental health. Emissions in the high-frequency blue-light range affects the circadian cycles of humans and animals and may also have effects on plants physiology. The emissions of LEDs used for public lighting such as streetlights in the high-frequency blue-light range have therefore been raised as a public health concern, in addition to increased glare and light pollution from LED streetlights. A “Dark Sky” movement advocates for minimal or no short-wavelength blue frequencies in public lighting (IDA (International Dark-sky Association), 2010), and the American Medical Association issued a report recommending that Color-correlated Temperatures (CCTs) be below 3,000 K – i.e. that public lights be kept in the “warm” range of color, closer to the red-light end of the emissions spectrum, to avoid interfering with circadian cycles (AMA (American Medical Association), 2016). The National Academies made a formal finding that researchers should continue investigating

these problems and developing solutions (National Academies of Sciences Engineering and Medicine, 2017).

Control systems combined with highly directional lighting can enable one luminaire to accomplish the work of many luminaires; using sensors and network controls, beams from a single lamp could be directed to places where light is needed instead of requiring multiple lamps to illuminate the same spaces. For example, sensors could direct light from a single lamp along sidewalk paths only when pedestrians are walking there (OSRAM, 2015). In addition, Combining lights with sensors has been explored in hopes of enabling such applications as streetlights that combine as-needed efficient lighting with crime-detection and automated reporting to authorities (Murthy, Han, Jiang, & Oliveria, 2015).

With climate change on the rise and global food security on the decline, the benefits of being able to grow crops outside of their normal environments are rapidly rising (Weber & Matthews, 2008). Other types of lamps have been used to grow plants indoors and out of their usually climates (Duke, Hagin, Hunt, & Linscott, 1975; Helson, 1965), but new research is showing that you can use LEDs more effectively for the same purpose (Kim, Hahn, Heo, & Paek, 2004). LEDs are well-positioned to be the best product for horticultural lighting because of their high efficiency and their excellent ability to control color – plant growth responds better to certain frequencies (i.e. colors) of light (McCree, 1972), and the ability of LEDs to optimize exact light frequencies so as to maximize plant growth is a strong advantage over other options for horticultural lighting. Figure 45 shows an example of LEDs being used for horticultural lighting at frequencies that don't seem aesthetically appealing but nevertheless promote strong plant growth.



Figure 45: An example of LEDs being used for horticultural lighting at frequencies that don't seem aesthetically appealing but nevertheless promote strong plant growth. Source: Mattison, 2016

One emerging application of LEDs involves re-purposing them for communication instead of illumination. Under the umbrella term of Visual Light Communication (VLC), or “Li-Fi,” LED light sources are finely controlled at high-emissions frequencies to rapidly emit information in the same manner as that of radio waves in contemporary Wi-Fi technology. Potential exists for Li-Fi to be faster than Wi-Fi (Chi et al., 2015), possibly up to 100 times faster (“Li-Fi 100 times faster than Wi-Fi,” 2015). Challenges are that Li-Fi requires an uninterrupted path between the emitter and receiver, i.e. no walls or objects can be in the linear path of the signal (unlike Wi-Fi and radio which go through walls and other objects). An advantage is that Li-Fi is more difficult to detect without knowing in advance what the

path of the signal is, and if that path is enclosed (e.g. inside of a building) it cannot be detected using any instruments outside of the building due to the linearity of the signal, which minimizes potential for network intrusion (Grobe et al., 2013; Harbers & Manney, 2014; O'Malley, 2015). In automobiles, researchers have found ways to use LEDs and laser LEDs for car-to-car communication as a further example of Li-Fi or VLC. Because the beams from LEDs are linear rather than omnidirectional, systems can be designed to use LEDs for directional headlights that shine on the road and not into the eyes of oncoming drivers. Moreover, using highly efficient blue lasers to create white light has already been demonstrated and can be applied to increase automobile energy efficiency (National Academies of Sciences Engineering and Medicine, 2017).

6.3.2 Where are markets for solid-state lighting products going next?

Globally, SSL represented 6 percent of the world's installed lighting at the end of 2015 (US Department of Energy, 2016c). LED sales have gone up in the past few years (National Research Council of the National Academies, 2013) and are projected to increase further - In 2020, it is projected that LED lamps will be 42 percent of unit sales, 76 percent of revenues, and one-third of the installed base of lighting technology.

Projections show significant growth in LED market shares ranging from 67 percent to 80 percent by 2022. Conventional lamps are being replaced with LEDs at an increasing rate, but because of the LEDs' long lifetimes sales are likely to decline after an initial wave of increased sales. Commodity lamp sales are expected to peak in 2020. Specialty products sales are expected to peak in 2022. LEDs sell fewer units but bring in more revenue

because they are priced higher (National Academies of Sciences Engineering and Medicine, 2017). Despite the increases in sales being an apparent success for the LED industry, some forecasts predict peaks in sales around 2020 and subsequent ~66% decline of industry revenue by 2030 (Pike Research, 2011). This could have huge impacts on employment in the SSL industry worldwide and perhaps especially in the US where much of the SSL industry's R&D is still performed (National Academies of Sciences Engineering and Medicine, 2017).

In the US, both the federal government and the California state government have been very pro-active with regulations on lighting during the Obama administration. The US Department of Energy has instituted several rounds of rulemaking to regulate lighting products' energy efficiency. One industry association has claimed that the subsequent rulemakings have had diminishing returns in terms of energy-efficiency gains⁴⁹ and increasing losses to suppliers' bottom line, offering an attempted visualization in support shown in Figure 46 (National Academies of Sciences Engineering and Medicine, 2017).

⁴⁹ See Kyle Pitsor, NEMA, letter to Brenda Edwards, U.S. Department of Energy, regarding Docket Number EERE-2011-BT-STD-0006, NEMA Comments GSFL IRL NOPR, June 30, 2014, <http://www.nema.org/Policy/Pages/Rulemaking-Comments.aspx>.

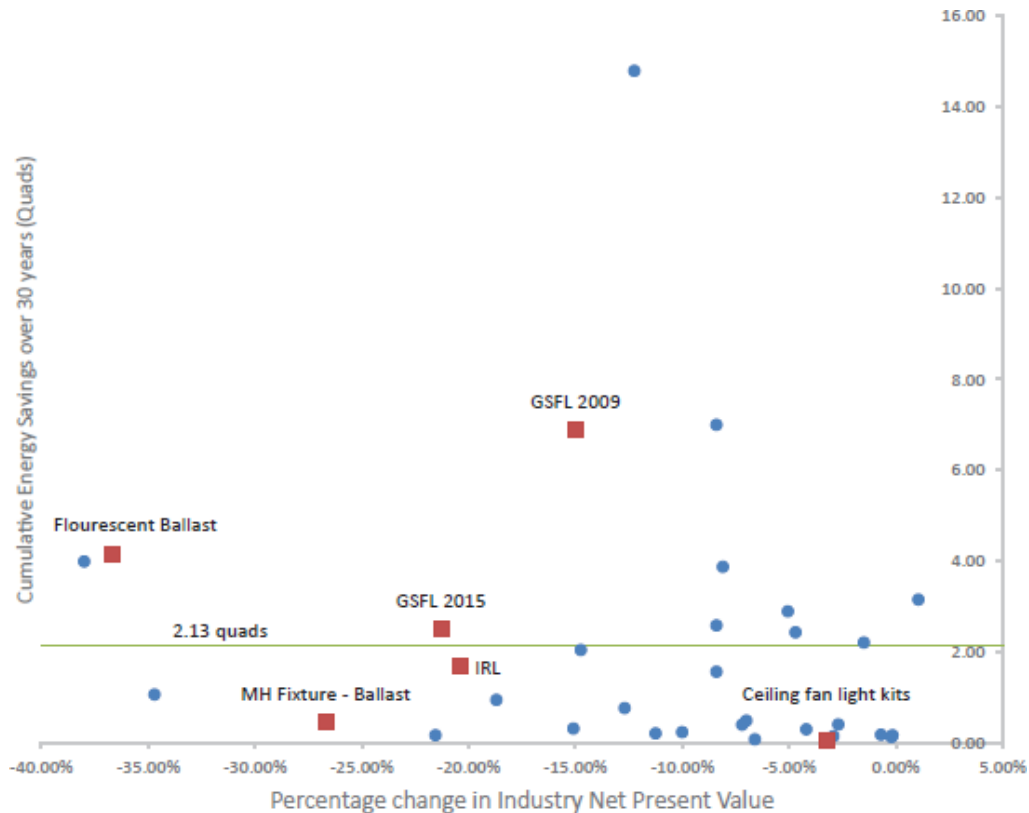


Figure 46: NEMA’s visualization offered in support of their claim that subsequent lighting efficiency rulemakings have had diminishing energy-efficiency returns.⁵⁰
Source: National Academies of Sciences Engineering and Medicine, 2017

On August 28, 2019, the US Department of Energy closed a rulemaking required by the US Congress’ Energy Independence and Security Act of 2007 (EISA 2007) that targeted energy efficiency for general service lamps without issuing a final rule. EISA 2007 requires the US Secretary of Energy to prohibit sale of any lamp below a 45lm/W efficacy (the

⁵⁰NEMA’s caption for the figure: “Effects of Department of Energy (DOE) rulemakings on energy savings and industry net present value. Data points indicate the manufacturing net present value of past rulemakings on lamps and ballasts (squares) and on other efficiency measures (circles). The horizontal line represents the average projected energy savings for DOE’s appliance efficiency rulemakings completed since 2008. The dots above the horizontal line show that some of the lighting rulemakings have contributed most significantly to the cumulative energy savings of these rulemakings, but there are some below the horizontal line that have only contributed marginally. NOTE: GFSL = general service fluorescent lamps; IRL = incandescent reflector lamps; MH = metal halide.”

“backstop standard”) if the US Secretary of Energy finds that an amendment to current regulations on general service lamps is necessary and the US Department of Energy failed to complete the rulemaking by January 1, 2020. Standards formerly proposed in the US Department of Energy’s rulemaking process would have had the effect of eliminating current CFL products in favor of current LED products for low-intensity applications (310lm to 2,000lm). The US Department of Energy has contended that the 45lm/W standard that would take effect if the rulemaking fails to conclude will automatically apply to each and every lighting product, but industry associations have contended that the 45lm/W standard refers to an average across all products sold by a given lighting supplier (a la CAFÉ standards for automobiles) (National Academies of Sciences Engineering and Medicine, 2017). Currently, the US Department of Energy contends that the backstop standard will not apply because necessary conditions identified in EISA 2007 for the standard to apply have not been met, but many commenters to the US Department of Energy’s February 2019 proposal to end the rulemaking without issuing a final rule contend that the conditions have been met and that the backstop standard will become binding statute as of January 1st, 2020 (US Department of Energy, 2019). The regulatory environment will continue evolving following likely litigation against the US Department of Energy’s decision.

The California Energy Commission, a state agency that promulgates regulations of consumer products, has used Title 20 of the California Code of Regulations to recently issue CEC’s own performance standards for consumer lighting technologies that became effective on January 1, 2018. CEC’s regulations are part of a broader effort to meet aggressive goals for energy efficiency set forth in the California legislature’s 2015 Clean

Energy and Pollution Reduction Act (National Academies of Sciences Engineering and Medicine, 2017).

With regards to building codes regulations, the American National Standards Institute (ANSI)'s American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 90.1-2016 is the first set of building codes to be based on LED technology characteristics for any applications. As of 2017, only Maryland, New Jersey, and Vermont state building codes had adopted the previous standards, ASHRAE 90.1-2013, which were still based on conventional lighting technologies. Under Title 24 Part 6 of the California Code of Regulations, California's CEC published a set of building codes in 2016 that were also based on LED technologies for some applications (National Academies of Sciences Engineering and Medicine, 2017).

With regards to regulations outside of the US, the European Commission (EC) directed suppliers to phase-out all directional incandescent lamps by 2016 and to phase-out all non-directional incandescent lamps by September 2018, with few exceptions that instead received higher efficiency and performance standards. The Japanese government has only instituted general policies toward energy efficiency that, for example, enforce efficiency performance for buildings as a whole. Despite these general standards, however, the Japanese market has transitioned to the world's highest penetration of LED technologies with LED luminaire products accounting for 70% of total luminaire sales. This largely occurred after the 2011 tsunami and subsequent shut-down of all Japanese nuclear power plants, increasing the costs of electricity to Japanese consumers. The Japanese government has previously proposed to ban all manufacture and imports of fluorescent lamps starting in 2020. Cuba was the first country to ban all filament lamps in 2005, and Australia phased

out traditional incandescent lamps in 2009 (National Academies of Sciences Engineering and Medicine, 2017).

6.4 What will lighting contribute to US economic growth and development?

In a 2016 report, the DOE SSL program exposes a looming question on whether SSL will follow the paths of other recent US-based clean-technology innovations by being developed in the US but manufactured and assembled outside the US. In the DOE SSL program's words: "to what extent will the U.S. economy also benefit from the robust business and job creation that will emerge as a result of the transition to SSL (SSL)?" Noting that the US and its public-private R&D partnerships have been at the center of technology development for the global SSL industry, the DOE SSL program's report acknowledged the global nature of manufacturing in the industry and the possibility that future SSL industry growth might not happen domestically. As an example, the DOE SSL program pointed to the history of the solar panel industry as an example of early US technology leadership that was appropriated by foreign firms and resulted in huge growth for the Chinese manufacturing sector (US Department of Energy, 2016a). Given the ties between manufacturing and economic growth, the manufacturing question becomes more broadly one of whether or not development of SSL technology can provide, or at least contribute to, sustainable economic growth.

6.4.1 Geographic distribution of the solid-state lighting industry

First, the sources indicate consistently that the SSL industry is a global one – the activities that go into producing SSL products are globally distributed and each involve global supply chains. Both the materials that go into the semiconductor components of SSL products and the tools used to process those materials are produced around the world. The DOE SSL program highlights this fact by presenting tables documenting the names of major firms involved in the SSL industry as of 2015. Table 26 presents the firms involved in producing the 3 major manufacturing components of SSL products – die manufacturing, package manufacturing, and luminaire (finished product) manufacturing. Table 27 presents the firms involved in the supply of materials and equipment necessary to carry out each of Table 26’s three manufacturing categories. From both tables, the large presence of firms in Asia is immediately noticeable. In most categories for both tables, Asia holds the largest number of firms or is tied for the largest number of firms with either North America or Europe (US Department of Energy, 2015, Section 8.3).

Despite the clear illustration of a global SSL industry implied by the tables, reason still exists to hold open the possibility that SSL could foster regional economic growth. Of note is that the tables’ regional classifications only represent where a firm is headquartered and not (necessarily) where the firm conducts its manufacturing activity (US Department of Energy, 2015, Section 8.3).. As learned in this dissertation’s earlier chapter on the histories of Philips and Hewlett-Packard, both companies have long ago globally distributed both their R&D and manufacturing. As such, reasons still stands to believe that, despite the tables on where SSL industry firms are headquartered, SSL R&D and manufacturing might still lead to regional economic growth.

Table 27: The LED Supply Chain - LED Die, LED Package, and Luminaire Manufacturers. Source: US Department of Energy, 2015

| Supply Chain | North America | | Europe | Asia | | |
|----------------------------------|---|--|--|---|--|--|
| Die Manufacturing | <ul style="list-style-type: none"> • Cree • Lumileds • Bridgelux | <ul style="list-style-type: none"> • Sora • SemiLEDs • Luminus Devices | <ul style="list-style-type: none"> • OSRAM Opto Semiconductors • Optogan • Plessey Semiconductors | <ul style="list-style-type: none"> • Nichia • Toyoda Gosei • Toshiba • Sharp • Epistar • SemiLEDs Optoelectronics • MLS Lighting | <ul style="list-style-type: none"> • OptoTech • FOREPI • Everlight • Lumens • Kingbright • Samsung | <ul style="list-style-type: none"> • LG Innotek • Seoul Semiconductor • Elec-Tech Opto • Epilight • HC SemiTek • Sanan Optoelectronics |
| LED Package Manufacturing | As above | | As above | <ul style="list-style-type: none"> As above and: • Lite-On • Unity Opto • Lextar | | <ul style="list-style-type: none"> • Nationstar • Shenzhen Jufei • Honlitrone • Refond |
| Luminaire Manufacturing | <ul style="list-style-type: none"> • GE Lighting • Eaton/Cooper Lighting • Hubbell Lighting • Sora • MSI • Kim Lighting | <ul style="list-style-type: none"> • Acuity Brands • Cree Lighting Science Group • Feit | <ul style="list-style-type: none"> • Philips • Osram Sylvania • Zumtobel | <ul style="list-style-type: none"> • Panasonic • Toshiba • Sharp • LG • Samsung • Forest Lighting | <ul style="list-style-type: none"> • Kingsun • Zhejiang Yankon • Shenzhen Changfang • Oppl Lighting • PAK Corp • Nationstar • NVC Lighting Tech Corp • FSL | |

Table 28: The LED Supply Chain - Equipment and Materials Suppliers (continued over two segments). Source: US Department of Energy, 2015

| Supply Chain | North America | | | Europe | | Asia | |
|---------------------|---------------------------|---|--|---|---|--|--|
| Equipment Suppliers | Epitaxial growth | • Veeco Instruments | | | • Aixtron | • Taiyo Nippon Sanso | |
| | Wafer processing | • Plasma-Therm • Lam Research • Ultratech | • JPSA • Temescal | • Oxford Inst. Plasma Tech • EV Group • SUSS MicroTec • Logitech | | • Nikon Corp • Canon Inc. • Ushio Inc. | |
| | LED packaging | • Palomar Tech • Heller | • Nordson ASYMTEK | • Besi | | • ASM Pacific Tech • TOWA • Disco • Kulicke & Soffa (K&S) | |
| | Luminaire assembly | • Speedline Tech • Conveyor Tech | | • ASM Siplace • Assembleon | | • Panasonic • Fuji Machines | • Nutek |
| | Test and inspection | • KLA-Tencor • Cascade Microtech • Wentworth Labs • Orb Optronix | • Lighting Sciences Inc. • Gamma Scientific • Radiant Zemax | • SphereOptics • Daitron • Optest • Nanometrics • Chroma • Rudolph Tech • Labsphere | • Laytec • Bede • Bruker • Instrument Systems | • Cameca • SUSS MicroTec • Ismeca | • Quatek • Shibuya • Fittech Co • Panasonic • Fujikom • QMC |
| Supply Chain | North America | | | Europe | | Asia | |
| Materials Suppliers | Substrates | • Rubicon • Silian • Cree • Kyma | | • Monocrystal • Ammono • St. Gobain • Soitec | • Astek • STC • LG Siltron • Crystalwise Tech | • Air Water Inc. • TeraXtal • ProCrystal • Crystaland • Samsung | • Kyocera • Namiki • Mitsubishi Chem Corp • Hitachi Cable |
| | Chemical reagents | • SAFC Hitech • Dow Electronic Materials • Air Products | • SAES Pure Gas • Pall Corporation | • AkzoNobel • Linde Industrial Gases • Air Liquide | • Showa Denko KK • Matheson Tri Gas | | |
| | Packaging | • Bergquist Company • Cambridge America • CofanUSA • Indium Corp. | • DuPont • Laird Tech / • Cookson Electronics | • Heraeus | • Chin-Poon • Gia Tzoong • HolyStone • Iteq • Leatec | • Polytronics Tech • TA-I Tech • Tong Hsing • Univacoco Tech • Taiflex | • Viking Tech • Zhuhai • Totking • Denka • Kyocera • NRK |
| | Phosphors/Down-converters | • Intematix • Dow Electronic Materials • Philips Lumileds (internal) • GE (internal) | • Phosphortech • QD Vision • Nanosys • Pacific Light Tech | • Merck • Osram Opto Semiconductors (internal) | • Nichia (internal) • Mitsubishi Chemical Corp • Shin-Etsu • Denka | | |
| | Encapsulation | • Momentive Performance Materials (InvisiSil) | • NuSil • Dow Corning | • Wacker Chemie (LUMISIL) | • Shin-Etsu | | |

Based on discussions with industry experts, the National Academies claim that supply chain and cost reasons lead to most of the LED device fabrication for high-power LEDs being hosted in Asia. For low-power and mid-power LEDs, the National Academies claim

that the largest suppliers are a Taiwanese company called “Epi Star” and a Chinese company called “San’an”. The National Academies note that wafer fabrication, wafer dicing, and contact metallization are usually done in-house to safeguard the manufacturer’s processing trade secrets – in other words, there is no supply chain for this aspect of SSL production (National Academies of Sciences Engineering and Medicine, 2017).

6.4.2 Current state of the global solid-state lighting industry and its markets

The National Academies of Science, Engineering, and Medicine provide further insight into the state of the SSL industry and its likely prospects for driving regional economic growth. The National Academies’ assessment paints a picture of an industry reeling from price declines but finding new applications and niche markets offering potential growth. The National Academies claim that the SSL industry faced a condition of oversupply of commodity LED lamps for the past few years and has been restructuring to accommodate the situation. Citing to DOE reports (US Department of Energy, 2016b), the National Academies claim that, between 2013 and 2016, the price of LED lamps declined rapidly due to a subsidized increase in output from Chinese firms in the SSL supply chain. The National Academies claim that, from 2010 until 2017 (and possibly beyond), the Chinese government provided enormous subsidies to investments in Metal-organic Chemical Vapor Deposition (MOCVD) equipment, a key component for growing SSL dies. The resulting over-production of LED elements and subsequent overproduction of LED commodity lamps led to massive and disruptive price declines. Simultaneously, demand for commodity LEDs fell as LED-powered LCD displays became replaced with Organic LEDs (OLEDs) for back-lighting smartphone displays and large LED displays began requiring a smaller number of higher-powered LED elements. The National Academies note that the resulting

price decline has helped put commodity LED products on a more even footing with competition from CFLs and foreshadows the end of incandescent bulbs and conventional fluorescent lighting (National Academies of Sciences Engineering and Medicine, 2017). Figure 47 shows some evidence for this, illustrating the decline in the cost-per-unit-of-illumination and the corresponding increase in total US installations for LED commodity lamps (aka LED A-Type lamps).

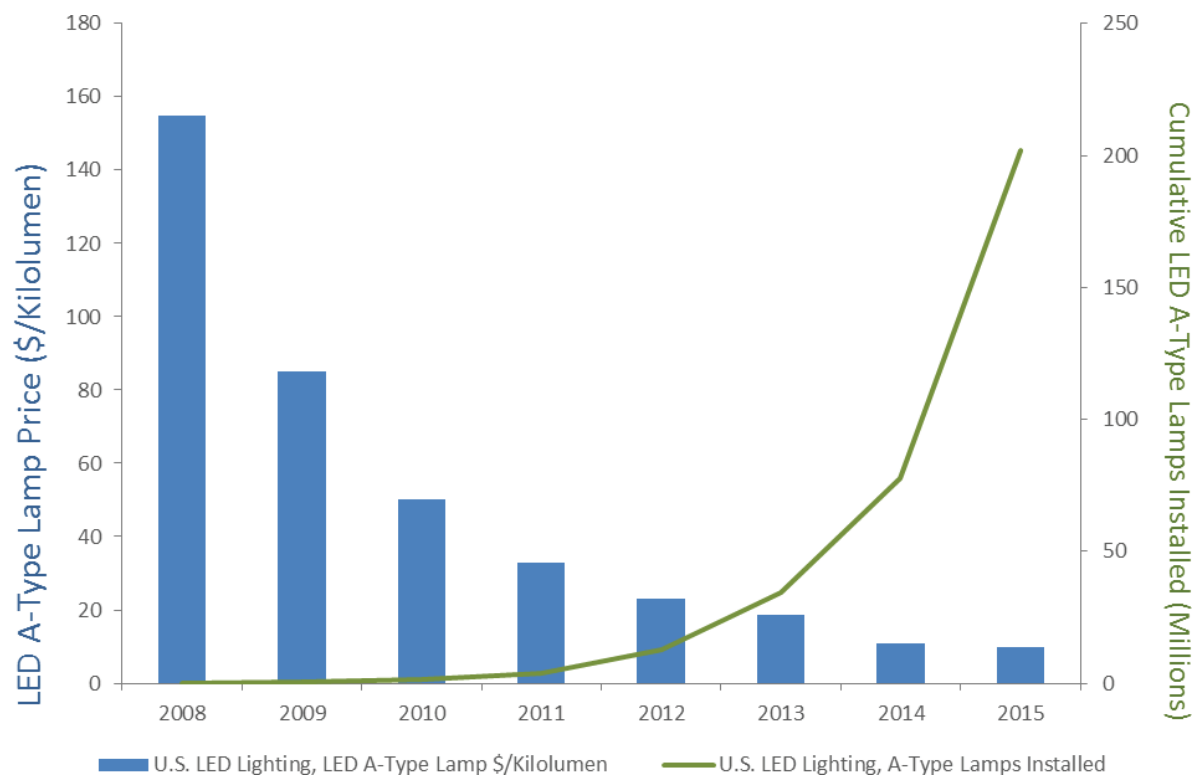


Figure 47; Between 2008 and 2015, a decline occurred in the cost-per-unit-of-illumination along with a corresponding increase in total US installations for LED commodity lamps (aka LED A-Type lamps). Source: US Department of Energy, 2016b

With the decline in prices, however, affected members of the global SSL industry have also faced a decline in profits and have taken steps to re-structure. The National Academies

include Table 28 in their report, showing that all major SSL industry members saw declining or steady profits in 2015 – the midst of the LED commodity lamp price decline. The National Academies note that, as of 2017, an increasing number of firms in the Chinese market were either going out of business or merging with other firms; this led the National Academies to predict wider global industry consolidation. Moreover, the National Academies note that members of the industry have begun their separating commodity lamp production activities from their specialty lamp production activities. Many industry actors have divested or plan to divest their commodity lamp activities in the near future, seeing the commodity lamp business as presenting unattractive margins and little opportunity to differentiate one's products from competitor's products (National Academies of Sciences Engineering and Medicine, 2017). As examples of those who have divested, General Electric chose to separate its lamp production activities from its specialty product activities (Black, 2015), and OSRAM has divested its lamp production into a spin-off company (Prodhan, 2015). The National Academies expect firms who remain in the LED commodity lamps business to continue focusing on cost reduction but at the same time express skepticism about those firms laying out R&D investments to bring costs down given LED commodity lamps' relatively low margins. The National Academies claim that, instead, those firms still making commodity lamps have moved their manufacturing centers to low cost locations in Asia. In their report, the National Academies make a formal finding that domestic manufacturing of LED commodity lamps is financially infeasible for US firms. The National Academies also claim that all US-based manufacturers have either separated operations of their commodity lamps business from their specialty lamps business or

divested the commodity lamps business entirely (National Academies of Sciences Engineering and Medicine, 2017).

Table 29: Ranking of LED Manufacturers by Revenue: The Largest 10 Players in the LED Industry Saw Their Revenues Shrink or Stay Level. Source: Stephanie Pruitt, 2016, presentation at Strategies in Light, Santa Clara, CA, March 1-3

| Rank | Company | Location | 2015 Revenues (\$) | 2015 Share (%) | Growth in \$USD (%) | Growth in Local Currency (%) |
|------|---------------------|----------------------|--------------------|----------------|---------------------|------------------------------|
| 1 | Nichia | Japan | 2,297 | 15 | -6 | 7 |
| 2 | OSRAM Opto | United States/Europe | 1,248 | 8 | -4 | 15 |
| 3 | Lumileds | United States/Europe | 1,196 | 8 | 4 | 4 |
| 4 | Samsung | South Korea | 960 | 6 | -18 | -18 |
| 5 | Seoul Semiconductor | South Korea | 801 | 5 | 0 | 7 |
| 6 | Cree | United States/Europe | 655 | 4 | -16 | -16 |
| 7 | LG Innotek | South Korea | 625 | 4 | -29 | -24 |
| 8 | Everlight | Taiwan | 590 | 4 | -6 | -6 |
| 9 | Mulinsen (MLS) | China | 561 | 4 | 2 | 2 |

Given that commodity lamps are a high-volume, low-price market segment, many industry players are giving more attention to specialty market segments that frequently involve made-to-order SSL products or relatively niche applications. Some members of the industry are pursuing new applications (highlighted in a section above) such as integrating SSL control systems, using SSL products for communication, and medical applications for revenue growth. Fortunately for such firms, the adoption of LED specialty products is also increasing especially for street and outdoor lighting, retail lighting, and industrial lighting. Despite relatively low volumes relative to the commodity lamps market, the specialty SSL products market remains financially encouraging due to higher revenues (National Academies of Sciences Engineering and Medicine, 2017).

Importantly, the National Academies report highlights that the industry's turn to specialty SSL products for growth has led to some reversal of common globalization patterns and an increasing regionalization of production. For specialty products such as large outdoor lighting products and customizable/one-off products, firms have begun situating their manufacturing closer to demand to reduce lead-time and shipping costs – moving their manufacturing facilities from Asia and into North America. Moreover, the National Academies expects that the next generation of SSL products will possess a large number of diverse features that a customer can customize on order and further expects that such products will of necessity be increasingly manufactured locally (National Academies of Sciences Engineering and Medicine, 2017).

6.4.3 The Department of Energy's view on appropriating the economic benefits of SSL

Despite the global nature of the SSL industry, some firms have been motivated to locate some of their facilities in the US, and even in specific regions. The reasons for these decisions were revealed through DOE SSL discussions on how SSL could avoid becoming another story of US technology leadership turning into growth only for overseas manufacturers. The DOE SSL program asked industry executives to discuss what factors – including policy decisions – would most influence their decisions on where to invest capital and locate facilities. The executives mentioned six key factors that would affect their decision to locate in the US and offered examples of how each factor has in practice influenced an SSL industry firm's location decision (factors and examples discussed below are taken from US Department of Energy, 2016a).

Access to markets: Some executives chose to locate R&D in the US but use contract manufacturers to serve markets abroad out of a desire to reach multiple markets from one location, such as the MOCVD equipment maker Veeco Instruments who does R&D in New Jersey and contracts for manufacturing in New York and Singapore. Conversely, many executives reported a desire to locate manufacturing in the US for advantages in accessing US SSL markets, such as executives with the three largest US lighting manufacturers – Acuity Brands, Eaton-Cooper, and Hubbell.

Access to supply chains: Quality control and operational integration can motivate a firm to locate its facilities close to those of other firms in the SSL industry, as with the firm CREE's choice to source domestically for manufacturing of certain components. While much of the supply chain is drawn to Asia by the presence of the world's package manufacturing facilities, Finelite centers its supply chain in California. Finelite's executives claim that this has helped the firm respond to market requirements, possibly owing to the strong lighting product regulatory regime promulgated by California government.

Access to innovation: Access to skilled and highly specialized R&D labor also motivates a firm's choice of location. The former HP-Philips joint venture Lumileds locates in the US to recruit workers from top university's materials science schools. Lumileds also stays in the US in order to develop its technology further by collaborating intensively with Sandia National Laboratory and Brookhaven National Laboratory.

Intellectual property protection: Manufacturing in the US offers the distinct advantage of intellectual property protection, a factor that has influenced Lumileds and CREE who each have MOCVD operations located in the US to protect both patents and trade secrets/know-how for their production processes.

Labor costs, productivity, and quality: While some construct the high cost of US manufacturing labor as a key barrier to domestic manufacturing, that cost can be seen as a premium on the quality and productivity of US labor. Several SSL firms such as the UK firm Carclo and US firm TOGGLED have chosen to re-locate manufacturing in the US instead of other countries to access the skilled labor force.

Government incentives: While subsidies to manufacturing are relatively low in the US compared with other countries such as China, state and local tax incentives have successfully attracted firms such as CREE and Universal Display Corporation to locate R&D facilities in the US. In addition, Maryland's Cecil County has funded training for local LED manufacturer I-lighting alongside direct financial aid from the Maryland state government.

6.4.4 Can SSL contribute to US economic growth and global competitiveness?

Given these findings, it seems possible for a US-based SSL industry to emerge. The current SSL industry clearly has no regional nexus and remains globalized. Findings made by the National Academies give the impression that part of the SSL industry, such as LED packaging, will remain globalized through the near future and likely beyond. Yet the executives surveyed by the DOE SSL program indicate strongly that many local economic features influence where SSL industry firms locate their facilities. Particularly, the executives highlighted access to specialized labor and the presence of other members in the SSL supply chain as key attractors. Also, global trends away from commodity lamp production and toward growth in specialty SSL products appear to be driving greater regionalization of manufacturing and other components of the SSL supply chain. Advantages of being close to markets – another attractor highlighted by industry executives – appear likely to have a strong influence on firms’ facility location decisions in the near future.

Moreover, the industry already has a strong intermediary – the DOE SSL program itself, which has throughout its history been convening SSL industry members from diverse sectors (academia, industry, government, and non-profits) to focus on specific, commonly faced issues. Much of the activity driving the development of the DOE SSL program’s annual R&D plans (and formerly, annual manufacturing roadmaps) can be construed as the actions of an economic development intermediary. The political sensitivities would be strong and would require significant action to overcome, but – were the DOE SSL program to take its role to a regional level, the program could have strong potential to drive formation of a new US-based SSL industry. Politically, it might be most feasible for the DOE SSL program to adopt a role as regional intermediary in an economically distressed

region facing post-industrial decay and standing to benefit from a revitalization of R&D and manufacturing. However, it's difficult to conceive of such a region that would also bear certain advantages named by SSL industry executives as key attractors, such as strong presence of top universities for supplying skilled R&D labor, national laboratories to act as technology collaborators, and markets with growing demand for specialty SSL products. Nevertheless, the DOE SSL program should be lauded for the intermediary work it has already performed and for tackling head-on the question of how to return the economic benefits of the program's investments in SSL technology to US taxpayers in the form of a stronger SSL manufacturing presence and well-paying opportunities for skilled labor. Future work should consider how to introduce a regional (or regionalizing) intermediary to the US SSL industry.

REFERENCES

- 109th Congress. Energy Policy Act of 2005 (2005). United States of America.
<http://doi.org/10.1109/MIA.2007.265799>
- 5W LED delivers new benchmark in brightness. (2002, April 22). *EBN*.
- Agilent Shifts Sites. (2003, August). *III-Vs Review*, 16(6), 19.
- Agilent Technologies and Lumileds Lighting Announce Agreement to Co-Develop New LEDs. (2004, July 15). *Business Wire*. Palo Alto, CA.
- Agilent Technologies Completes Sale of Its Stake in Lumileds. (2005, November 29). *Business Wire*.
- Agilent Technologies Inc. Analyst Meeting - Final. (2006, December 12). *Fair Disclosure Wire*.
- Agilent Technologies to spin off SOC and memory test businesses. (2005, October). *Evaluation Engineering*, 10.
- Aho, C. M. (1988). Technology, Structural Change, and Trade. In R. M. Cyert & D. C. Mowery (Eds.), *The Impact of Technological Change on Employment and Economic Growth*. Cambridge, Massachusetts: Ballinger.
- Also in the news... (2004, August). *Laser Focus World*, 55.
- Alternative Technologies Have OE Lighting Products Manufacturers Scrambling For Market Share. (1998, November 30). *PR Newswire*.
- AMA (American Medical Association). (2016). *Report of the Council on Science and Public Health: CSAPH Report 2-A-16*. Chicago, Illinois.
- Amano, H., Sawaki, N., Akasaki, I., & Toyoda, Y. (1986). Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer. *Applied Physics Letters*, 48(5), 353–355.
- Applied Technology: Dialight tower lighting. (2002, May 1). *Broadcast Engineering*.
- Arora, A., Branstetter, L. G., & Drev, M. (2013). Going soft: How the rise of software-based innovation led to the decline of Japan's IT industry and the resurgence of Silicon Valley. *Review of Economics and Statistics*, 95(July), 757–775.
- Around the Circuit: Industry News. (2004, September). *Microwave Journal*.
- Avago Technologies' Envisium family of LEDs receive EE Times' ACE ultimate products

- of the year award. (2006, September 1). *Microelectronics International*.
<http://doi.org/10.1108/mi.2006.21823cab.014/full/html>
- Aylward, D. (2006). Innovation lock-in: unlocking research and development path dependency in the Australian wine industry. *Strategic Change*, 15(7/8).
- Baier, E., Kroll, H., Schricke, E., & Stahlecker, T. (2012). *The regional innovation system of Baden-Württemberg reconsidered: Path dependency and technological leadership*. Fraunhofer ePrints.
- Baldini, N. (2011). University patenting: patterns of faculty motivations. *TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT*, 23(2), 103–121.
<http://doi.org/10.1080/09537325.2011.543329>
- Ball, R. (2002, March 27). Mitsubishi to backlight monitors with LEDs. *Electronics Weekl.*
- Barnard, C. C. (1988, October). Now a LED Can Take On the Light Bulb. *Electronics*, 41.
- Becker, S., Beveridge, R., & Rohring, A. (2016). Energy transitions and institutional change: Between structure and agency. In L. Gailing & T. Moss (Eds.), *Conceptualizing Germany's Energy Transition: Institutions, Materiality, Power, Space* (pp. 21–42). London: Palgrave Macmillan. <http://doi.org/10.1057/978-1-137-50593-4>
- Bipartisan Policy Center. (2016). *Modeling the Evolving Power Sector and Impacts of the Final Clean Power Plan*.
- Black, T. (2015). GE splits lighting to form LED unit as \$5 billion in sales seen. *Bloomberg*.
- Blue LEDs brighten up. (2000, November 22). *Electronics Weekly*, p. 2.
- Boersma, K. (2002). *Inventing structures for industrial research: A history of Philips Nat.Lab*. Amsterdam: Aksant Academic Publishers.
- Brouwer, E., & Kleinknecht, A. (1999). Innovative output, and a firm's propensity to patent. An exploration of CIS micro data. *RESEARCH POLICY*, 28(6), 615–624.
[http://doi.org/10.1016/S0048-7333\(99\)00003-7](http://doi.org/10.1016/S0048-7333(99)00003-7)
- Brown, M. a, Levine, M. D., Short, W., & Koomey, J. G. (2001). Scenarios for a clean energy future. *Energy Policy*, 29(14), 1179–1196. [http://doi.org/10.1016/S0301-4215\(01\)00066-0](http://doi.org/10.1016/S0301-4215(01)00066-0)
- Brown, M. A., Kim, G., & Smith, A. M. (2016). *The Clean Power Plan and Beyond* (No. 89).
- Brown, M. A., Levine, M. D., Romm, J. P., Rosenfeld, A. H., & Koomey, J. G. (1998). Engineering-economic studies of energy technologies to reduce greenhouse gas emissions: Opportunities and challenges. *Annual Review of Energy and the*

*Environment*1, 23.

- Brown, M. A., & Li, Y. (2019). Carbon pricing and energy efficiency: Pathways to deep decarbonization of the US electric sector. *Energy Efficiency*, 12(2).
- Brown, M. A., & Sovacool, B. K. (2014). *Climate change and global energy security: Technology and policy options*. Boston, Massachusetts: MIT Press.
- Brown, M. A., & Wang, Y. (2015). Program evaluation and the need for new business models. In *Green Savings: How policies and markets drive energy efficiency* (pp. 115 – 138).
- Brown, M., Kim, G., Smith, A. M., & Southworth, K. (2017). Exploring the impact of energy efficiency as a carbon mitigation strategy in the U.S. *Energy Policy*, 109, 249–259.
- Buhanist, P. (2015). Path dependency in the energy industry: the case of long-term oil-indexed gas import contracts in continental Europe. *International Journal of Energy Economics and Policy*, 5(4), 934–948.
- Burtraw, D., Linn, J., Palmer, K., & Paul, A. (2016). *Approaches to Address Potential CO2 Emissions Leakage to New Sources under the Clean Power Plan*. Washington, D.C.
- Bush, S. (2000, May 31). Philips-Agilent joint venture sheds light on LED performance boost. *Electronics Weekly*.
- Bush, S. (2002a, January 9). Lumileds lights up for bicycles. *Electronics Weekly*.
- Bush, S. (2002b, June 26). LEDs can meet lighting test says Lumileds. *Electronics Weekly*.
- Bush, S. (2002c, November 13). Fraen lenses help Lumileds focus adjustable white lighting in homes. *Electronics Weekly*.
- Bush, S. (2002d, November 20). LED firms settle dispute. *Electronics Weekly*B.
- Bush, S. (2003a, February 19). 2,000 LEDs light up shoppers in London. *Electronics Weekly*, p. 3.
- Bush, S. (2003b, July 23). Researchers make white LEDs using quantum dot phosphors. *Electronics Weekly*.
- Bush, S. (2004a, January 21). LEDs debut in car headlights. *Electronics Weekly*, p. 1.
- Bush, S. (2004b, July 28). Agilent links with Lumileds to fill gap in LED market. *Electronics Weekly*, p. 1.
- Bush, V. (1945). *Science the Endless Frontier: A report to the President*. Washington, D.C.
- Cadillac's XLR Luxury Roadster Showcases Innovative HID and LED Lighting. (2003,

- February 27). *PR Newswire*.
- Caldwell, D. E. (2001, July 27). A brighter idea: Philips, Agilent joint venture LumiLeds offers enhanced LED technology. *The Business Journal*, p. 30. San Jose.
- Camera-phone flash LEDs illuminate subjects at 1 to 2 m. (2004, November). *Portable Design*, (November).
- Chabchoub, N., & Niosi, J. (2005). Explaining the propensity to patent computer software. *TECHNOVATION*, 25(9), 971–978.
<http://doi.org/10.1016/j.technovation.2004.02.015>
- Chi, Y., Hsieh, D., Tsai, C., Chen, H., Kuo, H., & Lin, G. (2015). 450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM. *Optics Express*, 23, 13051–13059.
- Chin, S. (2001, April 2). Lumileds Outshines CCFL Backlights -- Company Says Its LED-Based Technology Offers Better Color, Durability. *EBN*.
- Chin, S. (2002, August 26). LOWER VOLTAGE -- Kopin Shines Cyberlite On Blue Leds. *EB*.
- Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2000). *NBER WORKING PAPER SERIES PROTECTING THEIR INTELLECTUAL ASSETS: APPROPRIABILITY CONDITIONS AND WHY U. S. MANUFACTURING FIRMS PATENT (OR NOT) - Working Paper 7552*. Retrieved from <http://www.nber.org/papers/w7552>
- Colon, A., & Torres, T. (2017, January). The best smart light bulbs of 2017. *PCMag.com*.
- Color Kinetics Selects Lumileds' Luxeon Light Sources for New bColor Fixtures, Citing Luxeon's Industry-Leading Intensity Per LED. (2002, August 27). *PR Newswire*.
- Conway, K. M. (2002, August). LEDs Focus Design Interest at LightFair 2002. *III-Vs Review*, 15(6), 34–36.
- Cooke, P. (2005). Regional transformation and regional disequilibrium: New knowledge economies and their discontents. In G. Fuchs & P. Shapira (Eds.), *Rethinking Regional Innovation and Change: Path Dependency or Regional Breakthrough* (pp. 43–62). Springer.
- Coombs, R., & Hull, R. (1998). “Knowledge management practices” and path-dependency in innovation. *Research Policy*, 27(5), 237–254.
- Costlow, T. (2005, April 18). LED Outlook Brightens. *Design News*, pp. 35–38.
- Cunningham, S. W., & Porter, A. L. (2011). Bibliometric discovery of innovation and commercialization pathways in nanotechnology. *2011 Proceedings of PICMET '11: Technology Management in the Energy Smart World (PICMET)*, 1–11.

- Dannoritzer, C. (2010). *The Lightbulb Conspiracy*.
- de Rassenfosse, G., Guellec, D., & de la Potterie, B. van P. (2008). Motivations to Patent: Empirical Evidence from an International Survey. In Duysters, G and Kaminishi, K (Ed.), *PROCEEDINGS OF THE 5TH INTERNATIONAL CONFERENCE ON INNOVATION & MANAGEMENT, VOLS I AND II* (pp. 2811–2819). 122 LUOSHI RD, WUHAN 430070, PEOPLES R CHINA: WUHAN UNIV TECHNOLOGY PRESS.
- De Vries, M., & Boersma, K. (2005). *80 years of research at Philips Natuurkundig Laboratorium (1914-1994)*. Amsterdam: Pallas Publications.
- Dechezlepretre, A., Glachant, M., & Meniere, Y. (2013). What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data. *ENVIRONMENTAL & RESOURCE ECONOMICS*, 54(2), 161–178. <http://doi.org/10.1007/s10640-012-9592-0>
- DeMeis, R. (2001, March 26). InGaN gains. *Design News*, p. 30. San Jose, CA.
- Dennis, M. (1997). Histiography of science: An American perspective. In J. Krige & D. Pestre (Eds.), *Science in the Twentieth Century*. Amsterdam: Harwood Academic Publishers.
- Double-brightness AlInGaN LEDs. (2001). *III-Vs Review*, 14(1), 20.
- Duguet, E., & Kabla, I. (2000). Appropriation strategy and the motivations to use the patent system: an econometric analysis at the firm level in French manufacturing. In Encaoua, D and Hall, BH and Laisney, F and Mairesse, J (Ed.), *ECONOMICS AND ECONOMETRICS OF INNOVATION* (pp. 267–305). 101 PHILIP DRIVE, ASSINIPPI PARK, NORWELL, MA 02061 USA: KLUWER ACADEMIC PUBLISHERS.
- Duke, W. B., Hagin, R. D., Hunt, J. F., & Linscott, D. L. (1975). Metal halide lamps for supplemental lighting in greenhouses: Crop response and spectral distribution. *Agronomy Journal*, 67(1), 49–53.
- Electric Power Research Institute. (2016). *State-Level Modeling of Clean Power Plan Compliance Pathways with EPRI's US-REGEN Model*.
- Epstein, R. a, & Kieff, F. S. (2011). Questioning the Frequency and Wisdom of Compulsory Licensing for Pharmaceutical Patents. *University of Chicago Law Review*, 78(1), 71–93.
- Essletzbichler, J. (2012). Renewable Energy Technology and Path Creation: A Multi-scalar Approach to Energy Transition in the UK. *European Planning Studies*, 20(5), 791–816.
- Event Brief of Q3 2004 Royal Philips Electronics Earnings Conference Call - Final. (2004,

November 12). *Fair Disclosure Wire*.

Fagerberg, J., Mowery, D. C., & Verspagen, B. (2009). *Innovation, path dependency and policy: the Norwegian case*. Oxford: Oxford University Press.

Fornahl, D., Broekel, T., & Boschma, R. (2011). What drives patent performance of German biotech firms? The impact of R&D subsidies, knowledge networks and their location. *PAPERS IN REGIONAL SCIENCE*, 90(2, SI), 395–U379.
<http://doi.org/10.1111/j.1435-5957.2011.00361.x>

Frondel, M., & Vance, C. (2013). Don't belittle the rebound effect. *Nature*, 494, 430.

Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2013). The Rebound Effect is Overplayed. *Nature*, 493, 475.

Gjelsvik, M., & Aarstad, J. (2017). Entrepreneurial industry structures and financial institutions as agents for path dependence in Southwest Norway: the role of the macroeconomic environment. *European Planning Studies*, 25, 406–424.
<http://doi.org/https://doi.org/10.1080/09654313.2016.1226786>

Grau, A. (2015, February). How to build a safer Internet of Things. *IEEE Spectrum*.

Grimm, H. M., & Jaenicke, J. (2012). What drives patenting and commercialisation activity at East German universities? The role of new public policy, institutional environment and individual prior knowledge. *JOURNAL OF TECHNOLOGY TRANSFER*, 37(4), 454–477. <http://doi.org/10.1007/s10961-010-9195-2>

Grobe, L., Paraskevopoulos, A., Hilt, J., Schulz, D., Lassak, F., Hartlieb, F., ... Langer, K.-D. (2013). High-speed visible light communications systems. *IEEE Communications Magazine*, 51(12), 60–66.

Gruber, W., Mehta, D., & Vernon, R. (1967). The R&D Factor in International Trade and International Investment of United States Industries. *Journal of Political Economy*, Jan./Feb., 20–37.

Hagedoorn, J., & Schakenraad, J. (1992). Leading companies and networks of strategic alliances in information technologies. *Research Policy*, 21, 163–190.

Haitz, R., Kish, F., Tsao, J., & Nelson, J. (2000). *The case for a national research program on solid-state lighting (SAND2000-1612)*. Albuquerque, NM.

Halper, M. (2016, February). The IoT is not secure. *LEDs Magazine*.

Hanson, D. A., & Laitner, J. A. S. (2004). An investment analysis of policies that increase investments in advanced energy-efficient/low-carbon technologies. *Energy Economics*, 26(4), 739–755.

Harbers, G., & Manney, S. (2014, November). “Internet of Lights” meets Industrial

- Internet of Things. *Photonics Media*.
- Headlights Go Digital. (2003, May). *Advanced Transportation Technology News*, 12.
- Heger, D., & Zaby, A. K. (2013). The heterogeneous costs of disclosure and the propensity to patent. *OXFORD ECONOMIC PAPERS-NEW SERIES*, 65(3, SI), 630–652. <http://doi.org/10.1093/oep/gpt018>
- Helson, V. A. (1965). Comparison of gro-lux and cool-white fluorescent lamps with and without incandescent as light sources used in plant growth rooms for growth and development of tomato plants. *Canadian Journal of Plant Science*, 45(5), 461–466.
- HEWLETT-PACKARD: HP supplies SnapLED automotive lighting assembly for 2000 Cadillac Deville. (1999, October 12). *M2 Presswire*.
- Hicks, A. L., & Theis, T. L. (2014). An agent based approach to the potential for rebound resulting from evolution of residential lighting technologies. *International Journal of Life Cycle Assessment*, 19, 370–376. <http://doi.org/10.1007/s11367-013-0643-8>
- High-Brightness LED Market to Reach \$10.8 Billion by 2010, According to New Report. (2005, November 8). *PR Newswire*. Glen Allen, VA.
- High-flux LED backlights for LCD displays. (2001, May). *III-Vs Review*, (4), 29.
- Holgersson, M. (2013). Patent management in entrepreneurial SMEs: a literature review and an empirical study of innovation appropriation, patent propensity, and motives. *R & D MANAGEMENT*, 43(1), 21–36. <http://doi.org/10.1111/j.1467-9310.2012.00700.x>
- Holonyak Jr, N. (2013). The III–V alloy p–n diode laser and LED ultimate lamp. *Proceedings of the IEEE*, 101(10), 2158–2169.
- Holt, M. (2001, April). Power LEDs to plug gap to adoption of white lighting. *III-Vs Review*, 14(3), 44–47.
- Hounshell, D. A. (1996). The evolution of industrial research. In R. Rosenbloom & W. Spencer (Eds.), *Engines of Innovation: US Industrial Research at the End of an Era*. Boston, Massachusetts: Harvard Business School Press.
- House, C., & Price, R. (2009). *The HP phenomenon: Innovation and business transformation*. Palo Alto, California: Stanford Business Press.
- HP and Philips expand joint venture advance LED adoption. (1999). *III-Vs Review*, 12(4), 1999.
- Hu, A. G. (2010). Propensity to patent, competition and China's foreign patenting surge. *RESEARCH POLICY*, 39(7), 985–993. <http://doi.org/10.1016/j.respol.2010.04.006>

- Huang, L., Guo, Y., Porter, A. L., Youtie, J., & Robinson, D. K. R. (2012). Visualising potential innovation pathways in a workshop setting: the case of nano-enabled biosensors. *Technology Analysis & Strategic Management*, 24(5), 527–542. <http://doi.org/https://doi.org/10.1080/09537325.2012.674673>
- Hussler, C., & Penin, J. (2012). Proactive versus reactive motivations for patenting and their impact on patent production at universities. *INTERNATIONAL JOURNAL OF TECHNOLOGY MANAGEMENT*, 58(3-4), 213–235. <http://doi.org/10.1504/IJTM.2012.046616>
- IDA (International Dark-sky Association). (2010). *Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting*. Tuscon, Arizona.
- IEEE engineers earn national medals of science, technology. (2003, December 4). *Electronic Design*.
- Jantz, R. (2019, November). Small Mitsubishi Projector More Toy than Tool. *PC World*, 23(11), 61.
- Johnstone, B. (2007). *Brilliant! Shuji Nakamura and the Revolution in Lighting*. Amherst, Massachusetts: Prometheus Books.
- Kim, S. J., Hahn, E. J., Heo, J. W., & Paek, K. Y. (2004). Effects of LEDs on net photosynthetic rate, growth and leaf stomata of chrysanthemum plantlets in vitro. *Scientia Horticulturae*, 101(1), 143–151.
- Kishi, N., & Takahshi, N. (2010). Licensing strategy of Japanese firms and competitive advantage. *Annals of Business Administrative Science*, 9(1), 1–12.
- Kivimaa, P., & Virkamaki, V. (2013). Policy Mixes, Policy Interplay and Low Carbon Transitions: The Case of Passenger Transport in Finland Policy Mixes, Policy Interplay and Low Carbon Transitions: The Case of Passenger Transport in Finland Policy Mixes, Policy Interplay and Low Carbon Transit. *Environmental Policy and Governance*, 24(1). <http://doi.org/https://doi.org/10.1002/eet.1629>
- Krey, M. (1990, May 7). HP 's quiet Components Group shines as maker of LEDs. *The Business Journal*, p. 9.
- Kwon, S., Porter, A. L., & Youtie, J. (2016). Navigating the innovation trajectories of technology by combining specialization score analyses for publications and patents: graphene and nano-enabled drug delivery. *Scientometrics*, 106(3), 1057–1071. <http://doi.org/https://doi.org/10.1007/s11192-015-1826-9>
- Lahoti, G., Porter, A. L., Zhang, C., Youtie, J., & Wang, B. (2018). Tech mining to validate and refine a technology roadmap. *World Patent Information*, 55, 1–18. <http://doi.org/https://doi.org/10.1016/j.wpi.2018.07.003>

- Langlois, R. N., Pugel, T. A., Harklisch, C. S., Nelson, R. R., & Egelhoff, W. G. (1988). *Microelectronics: An Industry in Transition*. Boston: Unwin Hyman.
- LED companies achieve IP cross-license accord. (2002, November 4). *EBN*, p. 16.
- LED companies respond to doubts over fitting quality. (2004, July 21). *Electronics Weekly*, p. 1.
- LED market brightens; tags fall. (2006, August 17). *Purchasing*.
- LED market lights up. (2000, August 24). *Purchasing*.
- LED outlook favors buyers. (2001, August 23). *Purchasing*.
- LED tags fall despite growing market demand (Optoelectronics). (2002, August 15). *Purchasing*.
- LEDs Light the Way for New Car Headlamp Designs. (2003, April 28). *PR Newswire*.
- Li, G. C., Lai, R., D'Amour, A., Doolin, D. M., Sun, Y., Torvik, V. I., ... Fleming, L. (2014). Disambiguation and co-authorship networks of the U.S. patent inventor database (1975-2010). *Research Policy*, 43(6), 941–955. <http://doi.org/10.1016/j.respol.2014.01.012>
- Li, X., & Ni, H. (2012). Intellectual property management and patent propensity in Chinese small firms. *INNOVATION-MANAGEMENT POLICY & PRACTICE*, 14(1), 43–58.
- Li-Fi 100 times faster than Wi-Fi. (2015, November). *BBC News*.
- Lighting firm develops 190 lumen LEDs for use in vehicle stop lights and indicators. (2005, April 6). *Electronics Weekl.*
- Link, A. N., & Ruhm, C. J. (2013). Fathers' patenting behavior and the propensity of offspring to patent: an intergenerational analysis. *JOURNAL OF TECHNOLOGY TRANSFER*, 38(3), 332–340. <http://doi.org/10.1007/s10961-012-9277-4>
- Literally Bluetooth. (2003, February 3). *Design News*, p. 38.
- Lumileds and Epistar Settle Lawsuit. (2004, July 12). *PR Newswire*. San Jose, CA.
- Lumileds Announces Luxeon 5-Watt, the World's Brightest LED Light Source. (2002, April 15). *PR Newswire*.
- Lumileds details 3W Luxeon LEDs. (2003, July 9). *Electronics Weekly*, p. 20.
- Lumileds Forms Luxeon Lighting Network to Aid Lighting Specifiers in Executing Projects Utilizing LED-Based Illumination Program Enables Manufacturers and Solution Providers to Exploit Exploding Market. (2004, March 31). *PR Newswire*. Las Vegas.

- Lumileds forms new Components Business Unit. (2000). *III-Vs Review*, 13(5), 21.
- Lumileds Introduces Luxeon III, an 80-Lumen Long-Life LED. (2003, October 13). *PR Newswire*.
- Lumileds Joint Venture Delivers Luxeon-based Products. (2005, May 1). *Electro Manufacturing*.
- Lumileds launches high-brightness LEDs. (2001, August). *III-Vs Review*, 14(6), 14.
- Lumileds Lighting and Philips Announce New Partnership. (2004, November 3). *Business Wir*, pp. 11–12. San Jose, CA.
- Lumileds Releases Reference Design for LED-Based Camera Phone Flash. (2003, August 11). *PR Newswire*.
- Lumileds Releases the First Ready-to-Use RGB LED Light Sources for Backlights. (2004, March 3). *PR Newswire*. San Jose, CA.
- Lumileds Ships Industry's First Warm White LED. (2003, October 27). *PR Newswire*. San Jose, CA.
- Lumileds Sues Epistar for Patent Infringement. (2003, August 18). *PR Newswire*.
- Lumileds to Open New Plant in Malaysia, Tripling Production Capacity for Luxeon LEDs. (2004, May 12). *PR Newswire*. San Jose, CA.
- Lumileds Touts New Luxeon I High Power LEDs. (2005, April 12). *Wireless News*. Jacksonville, FL.
- Lumileds' LED-based Backlight System Will Power TFT-LCD Modules for Mitsubishi Electric, Offering Key Benefits for Monitor Manufacturers. (2002, March 19). *PR Newswire*.
- Lumileds' Luxeon Garners Recognition. (2005, June 5). *Wireless New*. Jacksonville, FL.
- Machlup, F. (1958). *An economic review of the patent system*. Retrieved from [http://books.google.de/books?id=Cz7bAAAAAAJ&nhttp://library.mises.org/books/Fritz Machlup/An Economic Review of the Patent System.pdf](http://books.google.de/books?id=Cz7bAAAAAAJ&nhttp://library.mises.org/books/Fritz%20Machlup/An%20Economic%20Review%20of%20the%20Patent%20System.pdf)
- Major LED companies Nichia, Lumileds sign cross-licensing deal. (2002, November 18). *HFN The Weekly Newspaper for the Home Furnishing Network*.
- Mattison, N. (2016). *LED Lighting for Plant Applications*. Cornell University.
- McCabe, M. J., & Gottlieb, P. A. (2006). Approval of Exceptional Circumstances Determination for Inventions Arising under the Solid State Lighting (SSL) Program. US Department of Energy. Retrieved from <https://eere-exchange.energy.gov/FileContent.aspx?FileID=805eb561-03f3-4927-90a3->

e63c6fb9e540.

- McCree, K. J. (1972). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agricultural Meteorology*, 9, 191–216.
- McElligott, T. (2005, August 15). Agilent Technologies spinning into control. *Telephony*.
- McLeod, J. (1994, February 14). HP makes LEDs brighter than incandescent bulbs. *Electronics*, p. 1.
- Mills, A. (2001). High-Brightness LEDs lighting up the future. *III-Vs Review*, 14(1), 32–37.
- Mills, A. (2005, April). Higher performance LEDs from Lumileds. *III-Vs Review*, 18(3).
- Mitsubishi Electric Announces Three LED-Based TFT-LCD Modules Powered by Lumileds' Luxeon Technology, Scheduled for 2003 Release. (2002). *PR Newswire*.
- MJ Bradley & Associates. (2016). *EPA's Clean Power Plan: Summary of IPM Modeling Results*. Boston, MA.
- Moore, N. (2016, May). Smart homes' security flaws found in popular systems. *Phys.org*.
- Moser, P., & Nicholas, T. (2013). Prizes, publicity and patents: Non-Monetary awards as a mechanism to encourage innovation. *Journal of Industrial Economics*, 61(3), 763–788. <http://doi.org/10.1111/joie.12030>
- Moser, P., & Voena, A. (2012). Compulsory Licensing: Evidence from the Trading with the Enemy Act. *American Economic Review*, 102(1), 396–427. <http://doi.org/http://dx.doi.org/10.1257/aer.102.1.396>
- Mowery, D. C., Nelson, R. R., Sampat, B. N., & Ziedonis, A. A. (2001). The growth of patenting and licensing by U.S. universities: an assessment of the effects of the Bayh–Dole act of 1980. *Research Policy*, 30(1), 99–119. [http://doi.org/https://doi.org/10.1016/S0048-7333\(99\)00100-6](http://doi.org/https://doi.org/10.1016/S0048-7333(99)00100-6)
- Mowery, D. C., & Rosenberg, N. (1989). *Technology and the Pursuit of Economic Growth* (1st ed.). Cambridge: Cambridge University Press.
- Murthy, A., Han, D., Jiang, D., & Oliveria, T. (2015). Lighting-enabled smart city applications and ecosystems based on the IoT. *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, 757–763.
- Nakamura, S. (1991). GaN growth using GaN buffer layer. *Japanese Journal of Applied Physics*, 30(10A), L1705–L1707.
- Nass, R. (2005, May). Displays get bigger, brighter yet toe the cost line. *Portable Design*, 11(5), 25.

- National Academies of Sciences Engineering and Medicine. (2017). *Assessment of Solid-State Lighting, Phase Two*. Washington, D.C.: The National Academies Press. <http://doi.org/10.17226/24619>
- National Bureau of Economic Research. (2012). *Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry*. Cambridge, Massachusetts.
- National Research Council of the National Academies. (2013). *Assessment of Advanced Solid-state Lighting*. Washington, D.C.: National Academies Press. Retrieved from http://www.nap.edu/openbook.php?record_id=18279&page=R1
- Nauman, M. (1994, March 6). Bright idea from Hewlett-Packard. *Chicago Tribune*, p. U6.
- Navigant Consulting. (2014). *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*. Retrieved from <http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energysavingsforecast14.pdf>
- NEC-Mitsubishi Electronics Display Launches Its First LED Backlit LCD Display at SID 2004. (2004, May 24). *PR Newswire*. Seattle, WA.
- NEC-Mitsubishi's LED Backlit LCD Display. (2004, June). *Systems Contractor News*, 11(6).
- Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Cambridge, Massachusetts.
- O'Malley, L. (2015, September). Smart lighting: The gateway to the connected home and IoT markets. *MaRS Discovery District*.
- Office of Energy Efficiency and Renewable Energy. (2016). *Solid-state Lighting R&D Plan*. Washington, D.C.
- Office of Energy Efficiency and Renewable Energy. (2017). *DOE Solid-state Lighting Program: Modest Investments, Extraordinary Impacts*. Washington, D.C.
- Ohr, S. (2005, August 22). Wall Street applauds breakup of Agilent. *Electronic Engineering Times*, p. 21.
- OIDA Annual Forum Promotes Energy and Industrial Optoelectronics Applications. (2006, December 12). *Business Wire*.
- Onufrey, K., & Bergek, A. (2015). Self-reinforcing Mechanisms in a Multi-technology Industry: Understanding Sustained Technological Variety in a Context of Path Dependency. *Industry and Innovation*, October, 1–29. <http://doi.org/10.1080/13662716.2015.1100532>

- Organization for Economic Cooperation and Development. (1986). *OECD Science and Technology Indicators No. 2: R&D, Invention, and Competitiveness*. Paris.
- Organization for Economic Cooperation and Development. (2012). Promoting the transition to green growth. In *OECD Green Growth Studies, Energy* (pp. 29–60). Paris: OECD Publishing. <http://doi.org/10.1787/9789264115118-5-en>
- OSRAM. (2015, May). OSRAM SYLVANIA Unveils OmniPoint—The Future of Flexible Controllable Light—at LIGHTFAIR International.
- Overton, G. (2005, October). Agilent Selling Lumileds to Philips. *Laser Focus World*, 47.
- Pacific Gas and Electric. (2017). *Energy Efficiency Business Plan: 2018-2025*. San Francisco, California.
- Pacific Gas and Electric. (2018). *Integrated Resource Plan*. San Francisco, California.
- Pajunen, K., & Fang, L. (2013). Dialectical tensions and path dependence in international joint venture evolution and termination. *Asia Pacific Journal of Management*, 30(2), 577–600. <http://doi.org/10.1007/s10490-011-9267-3>
- Palm, J. (2006). Development of sustainable energy systems in Swedish municipalities: A matter of path dependency and power relations. *Local Environment: The International Journal of Justice and Sustainability*, 11(4), 445–457.
- Park, S.-C., & Lee, S.-K. (2005). The national and regional innovation systems in Finland: from the path dependency to the path creation approach. *AI & SOCIETY*, 19(2), 180–195. <http://doi.org/10.1007/s00146-004-0305-2>
- Perez-Cano, C., & Villen-Altamirano, J. (2013). Factors that Influence the Propensity to Patent. *EMJ-ENGINEERING MANAGEMENT JOURNAL*, 25(3), 27–38.
- Perez-Luno, A., & Valle-Cabrera, R. (2011). How does the combination of R&D and types of knowledge matter for patent propensity? *JOURNAL OF ENGINEERING AND TECHNOLOGY MANAGEMENT*, 28(1-2), 33–48. <http://doi.org/10.1016/j.jengtecman.2010.12.003>
- Peters, J. C., & Hertel, T. W. (2017). Achieving the Clean Power Plan 2030 CO2 Target with the New Normal in Natural Gas Prices. *The Energy Journal*, 38(5). <http://doi.org/10.5547/01956574.38.5.jpjet>
- Philips Lumileds Lighting and Toyoda Gosei Ink Pact to Share LED Patents. (2006, April 4). *Wireless News*, p. 1.
- Philips-Hewlett Joint Venture Set. (1997, January 17). *The New York Times*, p. D4.
- Pike Research. (2011). *Energy Efficient Lighting for Commercial Markets*. Boulder, Colorado.

- Porter, A. L., & Cunningham, S. W. (2005). *Tech mining: Exploiting new technologies for competitive advantage*. New York, NY: Wiley.
- Porter, A. L., Guo, Y., Huang, L., & Robinson, D. K. R. (2010). Forecasting Innovation Pathways: The Case of Nano-enhanced Solar Cells. In *Proceedings of International Conference on Technological Innovation*.
- President Bush Awards Lumileds Lighting's Chief Technology Officer Dr. M. George Craford The 2002 National Medal of Technology. (2003, November 6). *PR Newswire*.
- Prodhan, G. (2015). Osram to separate from lamps and focus on automotive. *Reuters*.
- Progress on display. (2003, February). *Materials Today*, (February), 20.
- Pylak, K. (2015). Changing innovation process models: a chance to break out of path dependency for less developed regions. *Regional Studies, Regional Science*, 2(1), 46–72. <http://doi.org/10.1080/21681376.2014.979433>
- Q2 2006 Royal Philips Electronics Earnings Conference Call - Final. (2006, July 17). *Fair Disclosure Wire*.
- Q4 2005 Agilent Technologies Inc. Earnings Conference Call - Final. (2005, November 14). *Fair Disclosure Wire*.
- QuarkStar Inc. (2015). Roland Haitz: A Life. QuarkStar Inc.
- Rice, T. (2016). Building the Energy Efficiency Power Plan: TVA's 2015 IRP. In *2016 ACEEE National Conference on Energy Efficiency as a Resource*.
- Risser, R. J., & Cook, K. (2010). Memorandum of understanding between the United States Department of Energy (DOE) and the Next Generation Lighting Industry Alliance (NGLIA). US Department of Energy. Retrieved from <http://www.nglia.org/pdfs/DOE-NGLIA-MOU-Extension-April-2010.pdf>
- Risser, R. J., & Cook, K. (2012). Memorandum of Understanding between the United States Department of Energy (DOE) and the Next Generation Lighting Industry Alliance (NGLIA). Retrieved from http://energy.gov/sites/prod/files/2014/04/f14/mou-nglia_2012.pdf
- Risser, R. J., & Cook, K. (2014). Memorandum of Understanding between the United States Department of Energy (DOE) and the Next Generation Lighting Industry Alliance (NGLIA).
- Robinson, D. K. R., & Propp, T. (2008). Multi-path mapping for alignment strategies in emerging science and technologies. *Technological Forecasting & Social Change*, 75(4), 517–38.
- Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K.

- (2015). Energy system transformations for limiting end-of-century warming to below 1.5 degrees Celsius. *Nature Climate Change*, (5).
- Roos, G. (2005, March 14). High-brightness LED family hits the road for exterior auto apps. *Electronic Engineering Times*, p. 57.
- Sadin, M. (2003, July 28). Buggies with brights. *Newsweek*.
- Sandahl, L., Gilbride, T., Ledbetter, M., R.Steward, H. E., & Calwell, C. (2006). *Compact fluorescent lighting in America: Lessons learned on the way to market*. Richland, Washington.
- Sanderson, S. W., & Simons, K. L. (2014). Light emitting diodes and the lighting revolution: The Emergence of a solid-state lighting industry. *Research Policy*, 43(10), 1730–1746. <http://doi.org/10.1016/j.respol.2014.07.011>
- Sauer, J. (2005, March 1). Pocket Projection. *Sound & Video Contracto*.
- Scherer, F. M. (1977). *The Economic Effects of Compulsory Patent Licensing*.
- Schleich, J., Mills, B., & Dütschke, E. (2014). A brighter future? Quantifying the rebound effect in energy efficient lighting. *Energy Policy*, 72, 35–42. <http://doi.org/10.1016/j.enpol.2014.04.028>
- Scholvin, S. (2014). South Africa's Energy Policy: Constrained by Nature and Path Dependency. *Journal of Southern African Studies*, 40(1), 185–202.
- Shin-Etsu Handotai Obtains License Under Lumileds Patents. (3AD, August 11). *PR Newswire2*.
- Smith, A. M., & Brown, M. a. (2015). Demand response: A carbon-neutral resource? *Energy*, 85, 10–22. <http://doi.org/10.1016/j.energy.2015.02.067>
- Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy*, 37(4), 1356–1371.
- Sperling, E., & Chappell, J. (2002, November 25). Biggest Test. *Electronic News*, p. 22.
- Steele, R. (2003, January). High-brightness LEDs aglow for 2003. *Electronic Design*, 51, 1–2.
- Steranka, F. M., Defeverre, D. C., Camras, M. D., Tu, C., Mcelfresh, D. K., & Rudaz, S. L. (1988). Red AlGaAs light-emitting diodes. *Hewlett-Packard Journal*, 39(4).
- Stockton, D. (2001). Brighter, and better, lightbars: LED equipment lights the way. *Law & Order*, 49(7), 137–142.
- Strambach, S. (2008). Path Dependency and Path Plasticity: the Co-evolution of Institutions and Innovation - the German Customized Business Software Industry. In

- Strategies Unlimited Announces Program for Feb. 10-11, 2000 Conference On Business Opportunities in Advanced LEDs. (1999, November 18). *Business Wire*.
- Sullivan, L. (2003, August 11). Lumileds Develops LED-Based Flash For Camera Phones. *EBN*, p. 6.
- Suzuki, J., Gemba, K., Tamada, S., Yasaki, Y., & Goto, A. (2006). Analysis of propensity to patent and science-dependence of large Japanese manufacturers of electrical machinery. *SCIENTOMETRICS*, 68(2), 265–288. <http://doi.org/10.1007/s11192-006-0111-3>
- Szweda, R. (1999). What's in a name? *III-Vs Review*, 12(5).
- Szweda, R. (2002). 2002: the year in review. *III-Vs Review*, 15(9), 34–41.
- Tam, P. (2005, August 16). Agilent Unveils Restructuring Plan --- KKR , Silver Lake to Buy Chip Unit , While Philips Obtains Lumileds. *The Wall Street Journal*, p. B8.
- Tech Briefs. (2000, November). *Solid State Technology*, 40.
- Technology Brief -- Hewlett-Packard Co.: New Lights Might Replace The Incandescent Lamp. (1994, February 15). *The Wall Street Journal*, p. B5.
- Teece, D. J. (1993). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy*, 22(2), 112–113. [http://doi.org/10.1016/0048-7333\(93\)90063-N](http://doi.org/10.1016/0048-7333(93)90063-N)
- Teece, D. J. (1998). Capturing Value from Knowledge Assets. *California Management Review*, 40(3 Spring 1998), 55–79. Retrieved from <http://www.worldcat.org/oclc/206363502>
- Teresko, J. (2003, June). LEDs Redefine Lighting. *IndustryWeek*, 16.
- Toupin, L. A. (1999, October 4). LEDs hit the streets. *Design News*, p. 19.
- Toyoda Gosei and Philips Lumileds Share LED Patents. (2006, April 5). *JCNN News Summaries*.
- Tullis, T. K. (2005). Application of the government license defense to federally funded nanotechnology research: The case for a limited patent compulsory licensing regime. *UCLA Law Review*, 53, 279–313.
- Tyler, N. S. (2014). Patent nonuse and technology suppression: The use of compulsory licensing to promote progress. *University of Pennsylvania Law Review*, 162(2), 451–475. Retrieved from <http://www.scopus.com/inward/record.url?eid=2-s2.0-84893396321&partnerID=tZOtx3y1>

- UEC settles lawsuit - licenses Lumileds' T/S LED patents. (2001, October). *III-Vs Review*, 14(8), 20.
- US Department of Energy. (2006). *STATEMENT OF ANALYSIS OF DETERMINATION OF EXCEPTIONAL CIRCUMSTANCES FOR WORK PROPOSED UNDER THE SOLID STATE LIGHTING PROGRAM*. Washington, D.C.
- US Department of Energy. (2015). *Solid-state Lighting R&D Plan*. Washington, D.C.
- US Department of Energy. (2016a). *Prospects for US-based Manufacturing in the SSL Industry*. Washington, D.C.
- US Department of Energy. (2016b). *Revolution...Now: The Future Arrives for Five Clean Energy Technologies - 2016 Update*. Washington, D.C.
- US Department of Energy. (2016c). *Solid-state Lighting R&D Plan*. Washington, D.C.
- US Department of Energy. (2019). *10 CFR Part 430: Energy Conservation Program: Definition for General Service Lamps*.
- US Energy Information Administration. (2015). *Annual Energy Outlook 2015*. Washington, D.C.
- US Energy Information Administration. (2016). *Annual Energy Outlook 2016*. Washington, D.C.
- US Energy Information Administration. (2017). *Trends in Lighting in Commercial Buildings*.
- US Environmental Protection Agency. (2014). *Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants*. Retrieved from <http://www2.epa.gov/sites/production/files/2014-06/documents/20140602ria-clean-power-plan.pdf>
- Usselman, S. W. (1993). IBM and its Imitators: Organizational Capabilities and the Emergence of the International Computer Industry. *Business and Economic History*, 22(2).
- Vanecek, J. (2008). Patenting propensity in the Czech Republic. *SCIENTOMETRICS*, 75(2), 381–394. <http://doi.org/10.1007/s11192-007-1874-x>
- Wang, Y., & Brown, M. a. (2013). Policy drivers for improving electricity end-use efficiency in the USA: an economic–engineering analysis. *Energy Efficiency*, 7(3), 517–546. <http://doi.org/10.1007/s12053-013-9237-3>
- Warm white Luxeon LEDs by Lumileds Lighting. (2004, April). *Buildings*, 61.

- Weber, C. L., & Matthews, H. S. (2008). Food-miles and the relative climate impacts of food choices in the United States. *Environmental Science and Technology*, 42(10), 3508–3513.
- Wirbel, L. (1996, May 27). HP puts AlInGaP LEDs in flip-chip form. *Electronic Engineering Times*.
- Wolsink, M. (2012). The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources. *Renewable and Sustainable Energy Reviews*, 16(1), 822–835.
- World's Brightest LED from Lumileds Lighting Debuts at LightFair in San Francisco. (2002, June 3). *2PR Newswire*.
- Wright, E., & Kanudia, A. (2016). Variation in outcomes and leakage potential across Clean Power Plan compliance designs. *Energy Economics*, 60, 438–450. <http://doi.org/https://doi.org/10.1016/j.eneco.2016.06.016>
- Yosick, J. A. (2001). Compulsory patent licensing for efficient use of inventions. *University of Illinois Law Review*, 1275–1304.
- Youtie, J., Porter, A. L., Boyack, K., Lobo, J., Klavans, R., Rafols, I., & Shapira, P. (2012). Using Large-scale Databases to Understand the Trajectories of Emerging Technologies. In *Little by Little: Expansions of Nanoscience and Emerging Technologies* (pp. 55–58). Heidelberg, DE: Adakemische Verlagsgesellschaft.